IMPROVEMENT OF MINING EFFICIENCIES AT THABAZIMBI IRON ORE MINE

Sean James Rodger

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Johannesburg, 2005

DECLARATION

I, Sean James Rodger declare that this research report is my own, unaided work. It is submitted in partial fulfilment of the requirements for the degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other university.

Sean James Rodger
1 December 2005

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ABSTRACT

Significant research has been carried out over the years into what effect blast designs and techniques have on the final product in the mining process. There are numerous parameters that can be altered to deliver downstream benefits – the key is to determine which changes are appropriate for the rock body in question.

A project is currently underway at Thabazimbi Iron Ore Mine (Northern Province, South Africa) to improve the operational efficiency through attention to the blasting operation. Previous research suggests changing fragmentation will have an effect on mining efficiency, but no definitive model has been developed directly linking the two. Using data collected during the project, the author developed a sensitivity analysis tool, which defines the effect of changing fragmentation on overall mine efficiency. This prediction model was based partly on theory and partly on empirical information gathered from mine databases and personnel. Over the course of this project, this model was validated through the practical implementation of the theory behind its development. This involved decreasing powder factors through increasing the drilling pattern, thus changing the resulting fragmentation of the muckpile. Subsequently, downstream effects on mining efficiency were monitored and these results were recorded in the model.

The proven model was then used to identify areas of opportunity for improvement. In this report two areas are discussed, firstly, the implementation of a doped emulsion replacing ANFO across the mine, and secondly the introduction of electronic detonators. The second option would require further test work to develop confidence in the assumptions made in the model, concerning the effect of timing accuracy on fragmentation.

This research report covers the background to the project, an explanation of the model and the final results obtained.

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1 INTRODUCTION

This research report is based on a project carried out by the author at Thabazimbi Iron Ore Mine. The author is employed by African Explosives LTD (AEL) Blast Consult. AEL was requested by the mine to assist in improving the operational efficiencies and recoveries through attention to the blasting operation. This involved a process of benchmarking the current mining operation, proposing an improvement plan, and implementing and monitoring the changes.

The work carried out for the research project focused on issues identified as critical to evaluating the impact of blasting on the entire Thabazimbi mining operation. Waste mining constitutes the major part of the operation with a stripping ratio of around 10:1, and as such is a key area to improving efficiencies. This research focuses only on the waste mining component with ore mining to be considered at a later date. Neither milling nor beneficiation will be considered here.

Integral to this process was the evaluation of fragmentation distribution and the effect which varying fragmentation size has on the operational efficiency of the mine. This report outlines the background to this project and discusses the theory behind the need to define the correlation between fragmentation and operational efficiency. The concepts for creating a tool capable of this are detailed and each component of the resultant model is explained. This initial model is then validated by testing the theory through a series of test blasts. The results of these tests are then used to recalibrate the model and deductions are drawn from the model upon which recommendations are based.

1.1 <u>Background</u>

Thabazimbi Iron Ore Mine forms part of the Kumba Resources group. The mine is situated approximately 200km northwest of Johannesburg in the Northern Province. Thabazimbi provides iron ore (2 389 000 tonnes in 2003) for Iscor

Limited's steelworks in Vanderbijlpark and Newcastle. There are four pits in operation on the mine, namely Donkerpoort West, Buffelshoek West, Kwaggashoek and Donkerpoort Neck.

AEL supplies the mine with ANFO (Ammonium Nitrate Fuel Oil) and blasting accessories. The blast holes in which water is present use Bulk Mining Explosives' (BME) HEF100 (pure emulsion). This is because while ANFO is not water resistant, pure emulsions and doped emulsions display excellent water resistant characteristics. Wet holes are predominantly encountered at Donkerpoort West as the pit level is approaching the level of the water table. The other three pits use ANFO most of the time.

Ultimately it is intended by mine management to implement the recommendations for improvement on all the pit operations. However, the focus of this project was primarily on Donkerpoort West, where most of the test work was carried out. The main reason for this was a restriction on resources, making it difficult to carry out testing and monitoring work on all the pits simultaneously.

1.2 Rationale for the Research

Thabazimbi Iron Ore Mine required clarity to the question – are the blasting designs and techniques presently in use, delivering the most favourable results downstream in the mining process?

This was seen as an opportunity to conduct an investigation into blasting techniques and the effects which these techniques have on the overall efficiency of the mine.

2 LITERATURE REVIEW

Significant research has been carried out over the years into what effect blast design and technique changes have on the final product in the ‘mine to mill’ process. When considering designs and techniques there are numerous parameters, which can be altered to deliver downstream benefits. The key is to determine which changes are appropriate for the rock body in question.

This section reviews theories that have been presented in the past with respect to the principles of blasting, improvements in certain blasting operations as well as the monitoring of the total ‘mine to mill’ process. The final solution/s which are implemented may draw from some of the ideas discussed in this section, but will essentially be based on new ideas in respect to open-pit iron ore mining.

Although the majority of the literature review was conducted at the outset of the project, other texts were also scrutinised as the project progressed and different ideas were explored.

P.R. Michaud points out that the key factor, which has attached to it numerous downstream effects, is fragmentation. A relationship exists between the fragmentation produced in a blast and the blast design (including rock properties and geometry) as well as other downstream effects such as loading efficiencies and the screening sizes in the secondary crushing process (Michaud, Blanchet, 1996).

Blasting (chemical energy) is more efficient than mechanical energy or crushing and for this reason it is essential to design a blast to deliver the necessary size distribution.

Fragmentation size distribution impacts on the total operation and it is important to bear the following in mind for any future investigation: *“Mine profitability is often affected appreciably by the percentage of fines created. When iron ores are being mined, it is necessary to optimise the lumps:fines ratio of the product. In times of worldwide economic growth, iron ore operators have maximised the* *lumps:fines ratio. Provided there is a demand for its entire production, lumps can be marketed at a premium."* (Hagan, 1979). And again, iron ore fines are also sold at a reduced price and need to be pelletised to regain value (Scott, Cocker *et al.* 1996).

The economic effect of changes in fragmentation can be significant. Loading, hauling and crushing costs should reflect any improvements or negative impacts changes in fragmentation might deliver (Figure 1).

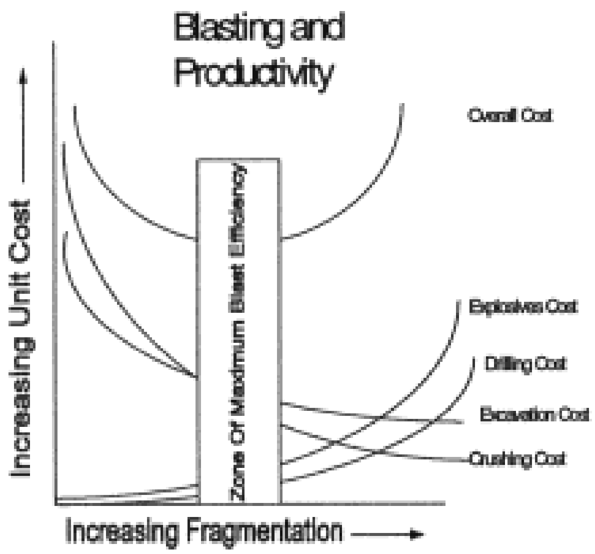

Figure 1: The Effect of Fragmentation on Costs (Bellairs)

W. Hustrulid argues that the idea of monitoring the mining system or process as a whole could provide an understanding of productivity, system efficiency as well as any improvements, which may be encountered throughout this process (Hustrulid, 1999).

Hustrulid also maintains that for the process to be improved, *"any group of people, machines or other elements that work together to do a certain job or accomplish a certain objective"* should interact ideally. He continues *"When the components or sub-systems interact significantly it may be possible to achieve that same final level of performance in many different ways. An enhanced or superior performance level in one sub-system may offset a lesser performance* *somewhere else along the chain. Once the system has been defined and the system goal(s) defined then the various means for achieving the final desired result may be studied. These optimisation studies, called 'trade-off studies', suggest how a given result may be achieved in the most economical manner."* (Hustrulid,1999).

S. Strelec asserts that these processes or systems, such as drilling, blasting and loading need to be considered separately, but also integrally to the whole. A change in the performance or results in one sub-system could impact negatively or positively on another system. For example, if drilling and blasting costs are minimal, there is a possibility that the costs following systems in the sequence (such as loading costs) could be significantly increased (Strelec, Bozic, Gotic, 2000).

The author maintains that the key concept in the success of the project is the idea of blasting to specification, where the ultimate requirement is defined at the outset and the respective designs and techniques are modelled accordingly. In this case the requirement will be defined through the benchmarking exercise and the development of the model, which will relate optimal efficiency with a particular blast design.

One sub-system within the blasting process is the initiation method and sequence of the blast. The blast result is determined primarily by the suitability of the timing design and the accuracy of the initiation system.

There are a number of important measures of blasting performance, including fragmentation. Changing certain aspects of the blast design, but particularly timing, usually has some influence on the following:

- Muckpile shape and digability
- Downstream handling
- Efficiency

At Thabazimbi Mine, blasts are usually designed to minimise lateral movement during blasting. The most effective timing pattern in producing the most desirable fragmentation distribution may not necessarily be ideal in terms of controlling muckpile displacement etc. Linked to this is the question of what muckpile shape best suits the loading equipment available. For a flat, low profile muckpile, a front-end loader may be best suited, whereas for a heaped muckpile a rope shovel (used at Thabazimbi) is the preferred option.

Claude Cunningham, AEL's Consulting Engineer, points out that Pyrotechnic systems are by their nature inaccurate, and blasting with such systems exposes the user to the potential for shots firing out of the planned sequence. In order to control blasting and to some extent pre-determine movement and fragmentation ranges, a more precise system is required. Electronic detonators (ED's) provide the solution. The precision of these systems is unrivalled, with the AEL's Smartdet® having a variation or a Coefficient of Variance (CoV) of 0.01% (Cunningham, 2000).

$$CoV = \sigma / T^m \times 100\%$$

Where

$\sigma =$ Standard Deviation

$T^m =$ Mean Delay

This is illustrated in Figure 2, which is a graph of the relative precision of timing systems (Cunningham, 2000).

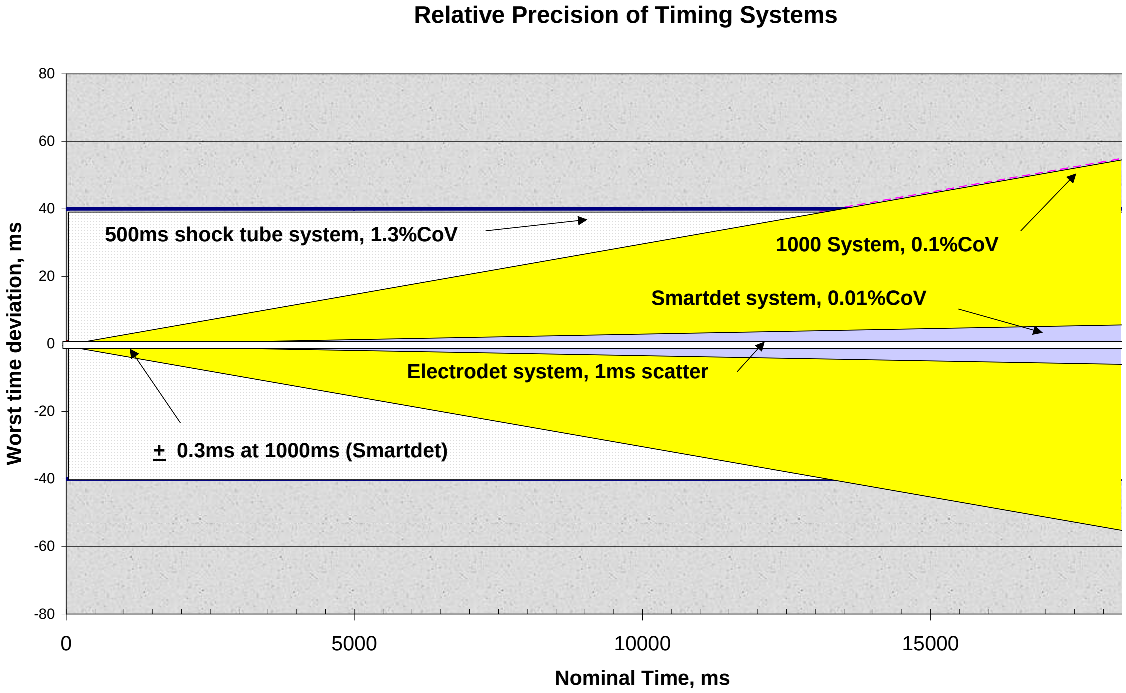

Figure 2: Relative Precision of Timing Systems

This accuracy as well as the unlimited range of delays achieved with the Smartdet® has resulted in improvements in a number of operations around the world. To improve blasting and ultimately mining efficiencies at Thabazimbi Iron Ore Mine, the key factor could be the timing of the blasts. In the ore blasts in particular, manipulation of timing may have an influence on the percentage of fine and oversize material produced. The Uniformity index (n) in the Rosin-Rammler equation gives a measure of this, with values greater than 1 indicating a more uniform sizing, whilst lower values result in higher proportions of fines and oversize. The Rosin-Rammler equation refers to the uniformity index (n) shown in equation 1.

$$\%\text{Passing} = 100 - \left(100 \times e^{-0.693 \times \left(\frac{Meshsize}{X_{50}}\right)^n}\right) \qquad \text{-------- Equation 1}$$

The uniformity exponent (n) is typically calculated from an equation developed by Cunningham (equation 2).

$$n = \left[2.2 - 14\left(\frac{B}{D}\right)\right]\left[0.5\left(1 + \frac{S}{B}\right)\right]\left[1 - \frac{Z}{B}\right]\left[0.1 + \frac{(L_b - L_t)}{L}\right]\left[\frac{L}{H}\right]P$$ ----- Equation 2

Where:

n is uniformity index

X_{50} is mean size (cm) – 50% passing

B is burden (m)

D is hole diameter (mm)

S is spacing (m)

Z is standard deviation of drilling error (m)

Lb is bottom charge length (m)

Lt is top charge length (m)

H is bench height (m)

P blast pattern factor (P = 1.0 for square pattern and 1.1 for staggered pattern)

From discussions with Claude Cunningham, it became apparent that a factor could be applied to the calculated uniformity index for pyrotechnic blasts to predict the fragmentation distribution from the same blast initiated with electronic detonators (Cunningham, 2005). This figure was taken to be 1.3 and can be applied with confidence, as the resultant fragmentation curve matches actual results achieved in the field[1]. It will be as a result of this accuracy and flexibility that there may be an avenue for improving the operating efficiency of the mine's excavation and also beneficiation processes (when considering ore), thus ultimately reducing operating costs and increasing revenue.

This research only covers waste blasting, but the effect of accurate timing in the control of ore blasting is another area for exploration. In terms of secondary crushing, the mine requires less fine material as well as more uniform size distribution. Findings from previous studies investigating the effect of electronic timing on fragmentation have shown that compared to pyrotechnic systems, there is a step change in the uniformity of the blasted product. A more uniform muckpile means a lower percentage of fines and oversize material and in turn

[1] From discussions with Claude Cunningham, AEL's Consulting Engineer (2004).

improved efficiencies often result. A number of published benefit cases can be seen in Appendix 1.

From the literature reviewed, it became evident that no attempt has been made to assign real values to graphs similar to the one shown in figure 1. There is also little or no information relating fragmentation size to loader or hauler productivity, and it is this information that is integral to the efficiency of the mining process. The difficulty with attempting to assign real values to such a graph is finding a mine site prepared to experiment with fragmentation sizes in both extremes, that is, predominantly fine and predominantly oversize material. This relationship between fragmentation size and unit cost can only be determined through measurement. The process of investigation revealed the need for a means of defining these relationships and it was this need that forms the basis of this research. The limitation to the extent of experimentation meant that a smaller window would have to be considered. In other words, not considering the full extent of the graph represented in figure 1, but instead a section of the graph, extending a certain limited distance, either side of the line of maximum efficiency.

The improvement of the blasting process and ultimately the mining process, as a whole, depends on the accurate capture of information. Through careful analysis of this information and the correct implementation of the most appropriate solution, the author hopes to improve the efficiency of the mining operation.

2.1 Proposition

To implement a step change in mining efficiencies at Thabazimbi Iron Ore Mine, through the application of new ideas and smart blasting techniques.

3 RESEARCH METHODOLOGY

The overall project carried out at Thabazimbi Mine was very broad and encompassed three phases, the benchmark or base case phase, the evaluation phase, and the development and validation of a prediction tool phase. A number of parameters were decided upon as necessary to measure and monitor, in order to define any improvements that may be experienced. Table 1 details these parameters as well as the method of measurement.

Table 1: Parameters and meaurables.

PARAMETER	MEASURABLE
Blast Design	Burden, Spacing, Hole Diameter, Bench Height etc.
Drilling	Metres
Initiation system	Units/hole
Explosives	Kg/hole
Geology	Models
Explosive and initiation system performance	VoD recordings and video and high speed analysis
Fragmentation	Photographic analysis – JK Split
Secondary Breaking	Pecker operating hours
Loading	Tons/hr
Secondary Crusher	Weightometer, percentage ‘lumps’, fines and slimes
Hauling Fuel consumption	Tons/litre
Vibration & Fly rock	Seismic monitoring and video and high-speed footage
Floor condition	Visual (Photographic)
Highwall condition	Visual (Photographic)

The research project and the work for the overall project at Thabazimbi was carried out concurrently and corresponded in some ways. However, the work for the research report focused principally on the blast design and blast results. The blasts results included loading efficiencies, secondary breaking and fragmentation in the muckpile.

Loading Efficiency

The mine-planning department acquires continuous loading and hauling figures from the hour meters and tonnage meters on the load and haul equipment. This information was captured for the relevant blasts.

Secondary Breaking

In order to determine the frequency of secondary breaking in each pit, the total working hours of the mechanical rock breaker, or ‘pecker’, was monitored.

Monthly explosive consumption was used as an indicator of the frequency of secondary blasting in each pit.

Fragmentation

Fragmentation analysis was carried out for each blast, and photographs of the muck pile were processed using SPLIT Desktop Fragmentation Analysis Software. For an explanation of the methodology of SPLIT software, see Appendix 2. When ore blasting is considered, it will be possible to monitor the movement of ore from a specific ore block blasted and analyse the size distribution, after secondary crushing, by a simple screening process. This process will evaluate the percentage of lumps, the percentage fines and the percentage slimes.

3.1 Conclusions

Once the methodology was established, the next stage involved the accumulation and analysis of required data. The next chapter details the results of this benchmarking exercise carried out at Donkerpoort West Pit.

4 BENCHMARKING

A benchmarking exercise was conducted in order to define and quantify the current mining operation. This stage of the project involved the capture of information relevant to all the mining operations. This information included current and historical production figures such as tonnages, machine hours and operating costs (including owning costs). Digital photographs of the muckpile were recorded for each of the blasts taken during the benchmarking phase of the project. These photographs were then analysed using Split Desktop fragmentation analysis software (Appendix 2).

The results were captured from the monitoring of a number of blasts as well as the analysis of historical data recorded over a period of six months.

4.1 <u>Drill and Blast</u>

4.1.1 Blast Parameters

Table 2 shows the planned blast parameters at Donkerpoort West Pit. Measurements taken during the benchmarking of hole depths, burden and spacing distances etc., revealed that controls on the drill and blast operation were in place, and were typically consistent with planned.

Table 2: Blast Parameters

Hole Diameter (mm)	251
Average Bench Height (m)	10
Sub-drill (m)	2.2
Burden (m)	5.2
Spacing (m)	6
Stemming material	Drill Chippings
Stemming height (m)	5
Explosive type	HEF100
Technical Powder Factor (kg/m³)	0.75
Initiation System (In-hole)	HM*25/500
Initiation System (Out-hole)	HTD**42

*HM is handimaster™ assembly

**HTD is handimaster™ trunk-line delay

4.1.2 Geology

At Thabazimbi Iron Ore Mine, waste is predominantly comprised of Oxidised Penge Banded Ironstone Formation (BIF) with areas of intrusion of a Diabase sill (Figure 3). The geologists map each ore block using information gathered from drilling blast holes, but no such mapping is carried out for the waste blocks. The block monitored during the benchmark (1000/4) was completely comprised of BIF and the information shown in Table 3 summarises the properties of this rock type based on compression tests.

Table 3: Geological Information

Mining Area	Rock Type	Density	Average UCS ± std. Dev. (MPa)	Young's Modulus (GPa)	Poisson's Ratio Secant
DPW	BIF	3.2	318.1 ± 100.6	95	0.14

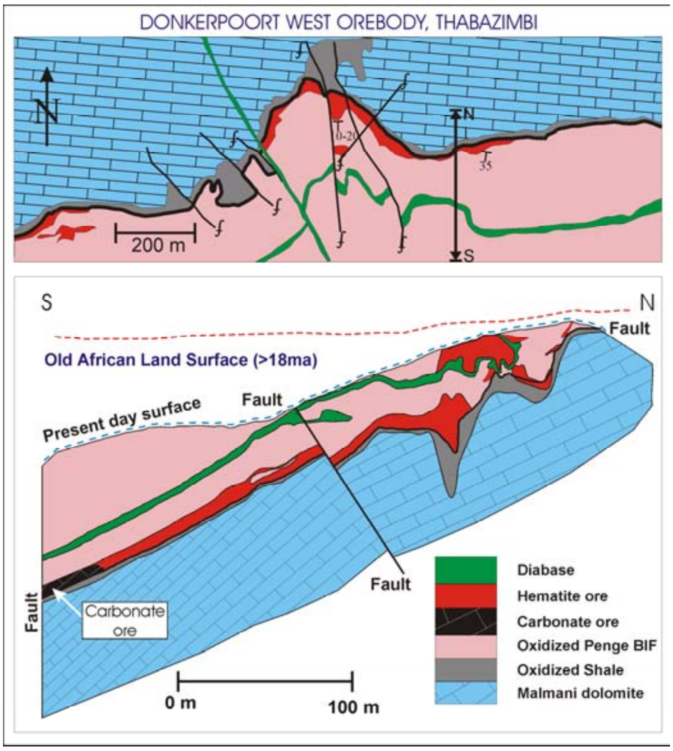

Figure 3: Geological Map of Donkerpoort West Pit

From the properties shown above the rock factor can be calculated. The rock factor is assessed for every rock type. As a result of the ore and waste in most areas on the mine being relatively weathered and friable, the functional rock factor in both the ore and the waste is taken to be 1.92.

For the purpose of calculations, a single density value for waste had to be chosen. In this case 3.2t/m^3 was used for waste rock.

4.2 Loading and Hauling

Each of the four operational pits on the mine has designated loaders and trucks. The Mine obtains continuous loading and hauling figures from the hour meters and 'tally'-ton meters on the relevant machinery. It is from this data that historical tons per hour figures, for the period July to December 2003, have been generated for Donkerpoort West Pit (Table 4). The historical loading rate is for the loading of both ore and waste. Also shown in Table 4, are the loading rates for the waste blocks, which were monitored for the benchmark.

Table 4: Loading Rates

	Waste 1000/4	**Historical**
Loading (Tons/hr) ± Std. Dev.	1005±233	941.5±64

For the waste block monitored only shovel 2300-01 was in operation. The historical average applies to all the loaders working in Donkerpoort West pit, namely, 2300-01 and 2300-03.

Loading rates will be used as an indication of any change in fragmentation, but the extent to which hauling rates will be affected by any change in fragmentation is difficult to determine. At the stage of the benchmark only diesel consumption was monitored.

4.3 Fuel

The mine records the total diesel consumption of the hauling fleet for each pit. For DPW the average diesel consumption rate is 56l/hr, which equates to 6 tons/litre. This average is calculated from the monthly figures for the period July to December 2003 and applies to both ore and waste.

4.4 Fragmentation

It is normally desirable to have uniform fragmentation (values of 1 or greater), thereby avoiding both excessive fines and oversize fragments in the broken ground. See section 2 (page 14) for an explanation of uniformity index.

A representative sample of images was taken of each muckpile. Split Engineering recommends that images be taken only of the outer surface of the blasted muckpile, as this delivers the most accurate (80%) representation of the fragmentation throughout the muckpile.

Figure 4 is the percentage passing graph of the waste block blasted (1000/4).

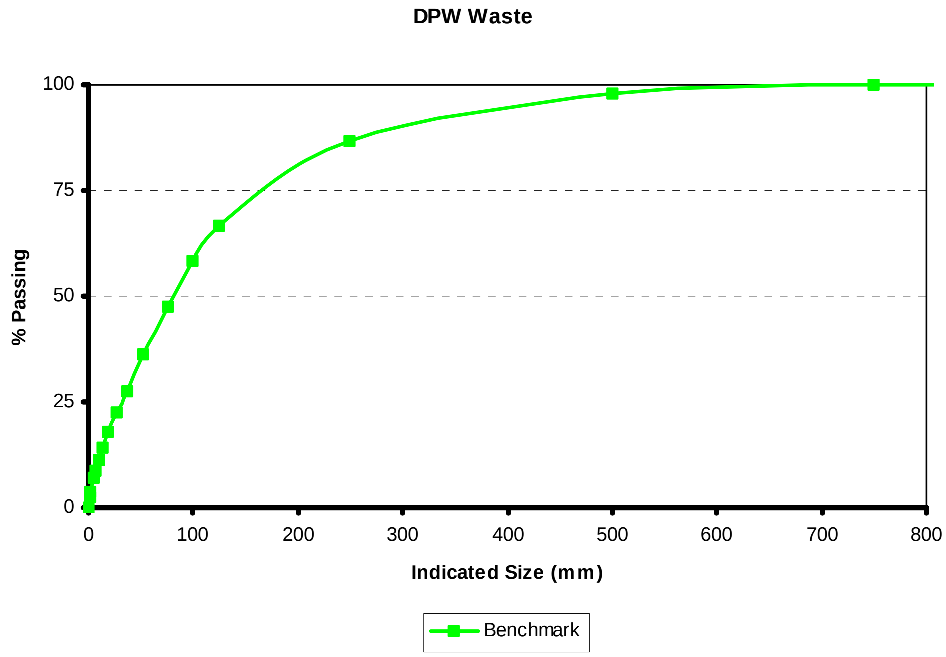

Figure 4: Percentage Passing vs. Indicated Size

A total of 45 images were taken across the muckpile. The calculated uniformity index *n,* for the sample analysed is 0.9 and the mean size, with 50% of the sample passing is 79.86mm. The detailed fragmentation results are shown in Appendix 3.

4.5 Secondary Breaking

In order to determine the frequency of secondary breaking in each pit, the total working hours of the mechanical rock breaker, or pecker, were monitored. A record is kept of the daily hours worked and the location (pit or crusher) of the machine. The hours recorded are total working hours and include hours for standing idle as well as the tramming hours, but should provide an adequate indication of secondary breaking. Also, the number of hours the machine operated at a specific location are not recorded, only the total hours for a specific day, so as an approximation, if the machine operated at more than one location in a day, the total hours worked would be divided by the number of locations worked, to determine the time worked at each location.

For the period July 2003 to January 2004, the average monthly secondary breaking hours for DPW pit was 46.9 hours. This equates to 2.3 hours per working day.

4.6 Highwall and Floor Conditions

Floor conditions are generally good with no evidence of toes, which has an effect on the wear-and-tear of tyres and tracks and also on general productivity.

The highwall was generally in a good condition, but no apparent barrels were visible (Figure 5). A couple of highwall failures were observed, but were clearly along geological faults, especially in friable and weathered ground conditions. With a highwall condition rating of good, average and poor, the resultant highwall in this case would rate as average.

Figure 5: Highwall Condition

There was evidence of back-break occurring as shown in Figure 6. Measured from the expected final highwall position, the average extent of back-break was 0.6m.

Figure 6: Evidence of Back-break

Table 5 summarises the results of this process

Table 5: Benchmark results

PARAMETER	RESULTS
	DONKERPOORT WEST
Geology (Density)	3.2t/m^3
Fragmentation - Uniformity (n) - Mean Size	 0.9 79.86mm
Secondary Breaking (Pecker hours)	2.3hours/day
Loading (tons/hour)	1005±233
Hauling Fuel consumption	6t/litre
Containment	Poor
Floor condition	Zero toes
Highwall condition - General - Back-break	 Average 0.6m
Drilling Costs	R0.52/ton
Explosives Costs	R0.71/ton
Loading Costs	R1.21/ton

4.7 Conclusions

This information captured during the benchmarking phase of the project was then scrutinised to determine areas where efficiencies could be improved and in order to fully understand what economic effect changes to the blasting operation would have on the mining operation as a whole. During this process it was discovered that in order to gain this understanding, a tool, capable of predicting the economic effect of changing fragmentation through altering the blast design, was required. The next chapter describes this tool.

5 THE INITIAL MODEL

Before focus could be given to the areas where opportunity for improvement was identified, it was decided to create a model, which would have the capability of predicting the effect of introducing changes to the blasting operation. This required a process of conceiving the idea for the model, presenting certain assumptions and validating the model through practical application.

The following sections discuss the philosophy of creating a tool that is capable of predicting the economic effect of changing fragmentation through altering the blast design, and the description of the primary model that was conceived.

5.1 Discussion

The principle of the model is the effect that changing fragmentation size has on operating costs per ton throughout all the relevant mining operations. From the benchmark, operating costs were calculated for the respective fragmentation distribution ranges for the various pits at that time. These fragmentation distributions were calculated using photographic analysis (Appendix 2, page 51). Mean Fragmentation size is predicted using the Kuz-Ram equation (Cunningham, 1983).

5.2 Description of the model

Essentially, the concept for creating the model was to analyse all the information that was captured in the benchmark and identify the most appropriate method of relating fragmentation distribution to each of the mining operations.

Fragmentation analysis during the benchmark revealed the typical distribution trends for the various pits. This information was entered into the SABREX blast design package to calibrate the system and the predicted rock characteristics were generated.

These rock properties were used with the Kuz-Ram (Equation 3) to calculate the fragmentation curves for various designs, based on certain input design parameters.

The Kuz-Ram equations are detailed below.

$$X_{50} = A \times \frac{Q^{1/6}}{K^{0.8}} \times \left(\frac{115}{REE} \right)^{0.633}$$ ---------- Equation 3

where

X_{50} = Mean size (cm) – 50% passing

A = Rock Factor

K = Technical Powder Factor (excluding sub drill) (kg/m³)

Q = Mass of explosive in blast hole (excluding sub drill) (kg)

REE = Relative Effective Energy of explosive

The formula for calculating the percentage passing various screen sizes is shown in equation 2 in section 2 (page 14).

The mean fragmentation size (Equation 1, page 14) was seen as the most appropriate measure to be used in the model. In order to generate different mean fragmentation sizes a change in the powder factor was required. For the model, it was decided to change the powder factor by altering the burden and spacing distances in the design. In association with this change, the sub-drill was also changed, in order to maintain the original burden to sub-drill ratio and control the final grade level.

The model is operated through Microsoft Excel and consists of a number of sheets with the input sheet being the main design sheet. A portion of this sheet is shown in Figure 7. The inputs required in the sheet are shown in green and the calculated values are shown in blue. Also generated in this sheet are the drilling and blasting (including explosives and initiators) costs. In order to calculate the drilling cost, the system requires a drilling cost per metre. This value is calculated on a separate drilling cost sheet where all the data relevant to drilling is entered. This sheet contains information such as machine hours, metres drilled, and the operating costs associated with certain drill rigs in the specific area under consideration. The operating costs are separated into mining costs and engineering costs.

Burden	4.45
Spacing	5.15
Burden ratio (hole diameters)	17.73
A	1.16
Sub-drill : burden	0.34
Hole Depth	11.53
Hole Angle	0.00
Hole Diameter	251.00
Bench Height	10.00
Bench Ht to Hole Diameter ratio	40
Stemming to Hole Diameter ratio	20
Tons per hole	733
Stemming Length	5.00
Sub-drill(u)	1.53
Charge above grade	5.00
Explosive Type	ANFO
Density	0.8
Kg Explosive per hole	258.39
Mc	39.59
Kact	1.13
Ktech	0.86
Rock Density	3.20
Surface IS Type and Length	HTD 10m
Quantity of HTD's	6
Total no of holes	150
Price/unit	17.27
HTD cost/hole	0.69
In-hole IS Type and Length	Handimaster 21m
Price/unit	48.74
Units/hole	1
Booster Type	400g Booster
Drilling cost per metre	63
Drill cost/hole	722.72
Drilling cost/ton	0.99
Blasting cost/ton	0.72
Cost/hole	1257.27
Cost/ton	**1.71**
Cost/m3	**5.49**
KUZ-RAM	
A	1.92
K	1.13
Q	258.39
REE	100
Mean Size (X)	4.82

Figure 7: Design Sheet

Mining costs consist of drill bits, drilling equipment and drilling accessories such as pipes and deck bushes. Engineering costs include services, repairs, maintenance, and miscellaneous costs as well as owning costs such as depreciation. Figure 8 shows the relationship that the model calculates for drilling cost and mean fragmentation.

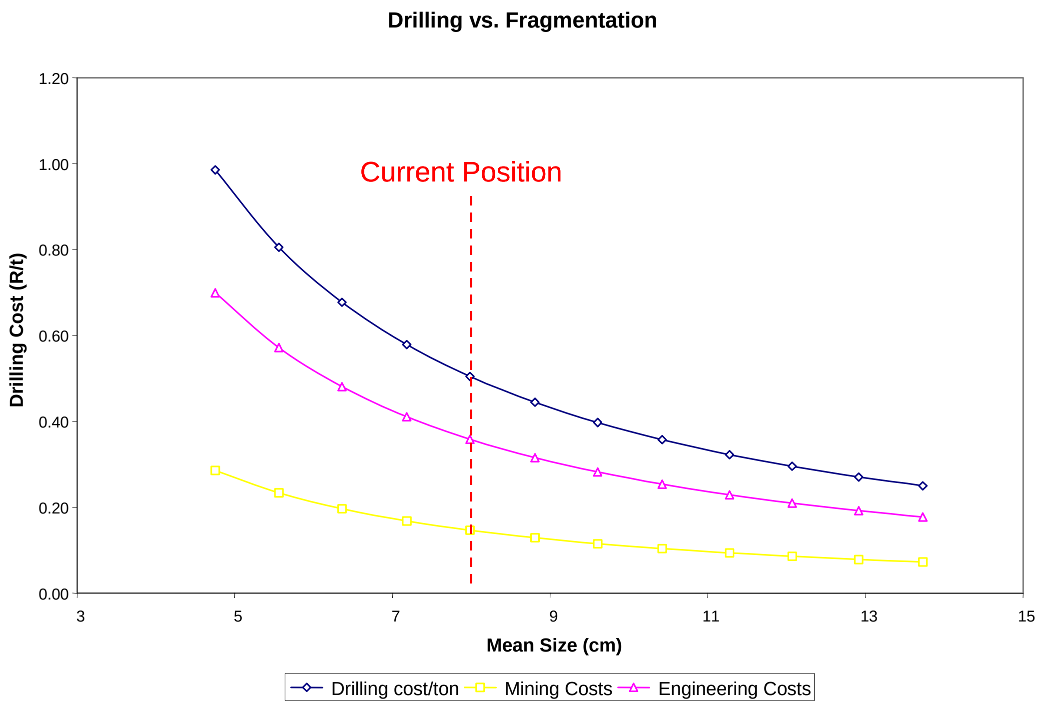

Figure 8: Drilling cost vs. mean fragmentation

The blasting cost is calculated on the principle of quantity per hole and this is linked to another sheet (Explosives and Initiation System units costs) where the actual cost, which the mine pays per unit (including handling costs) is sourced depending on the explosive or initiation type selected from the scroll down menu (figure 7). The system then calculates the relevant costs per ton for blasting. Figure 9 is a graphical representation of the relationship between blasting cost per ton and mean fragmentation size.

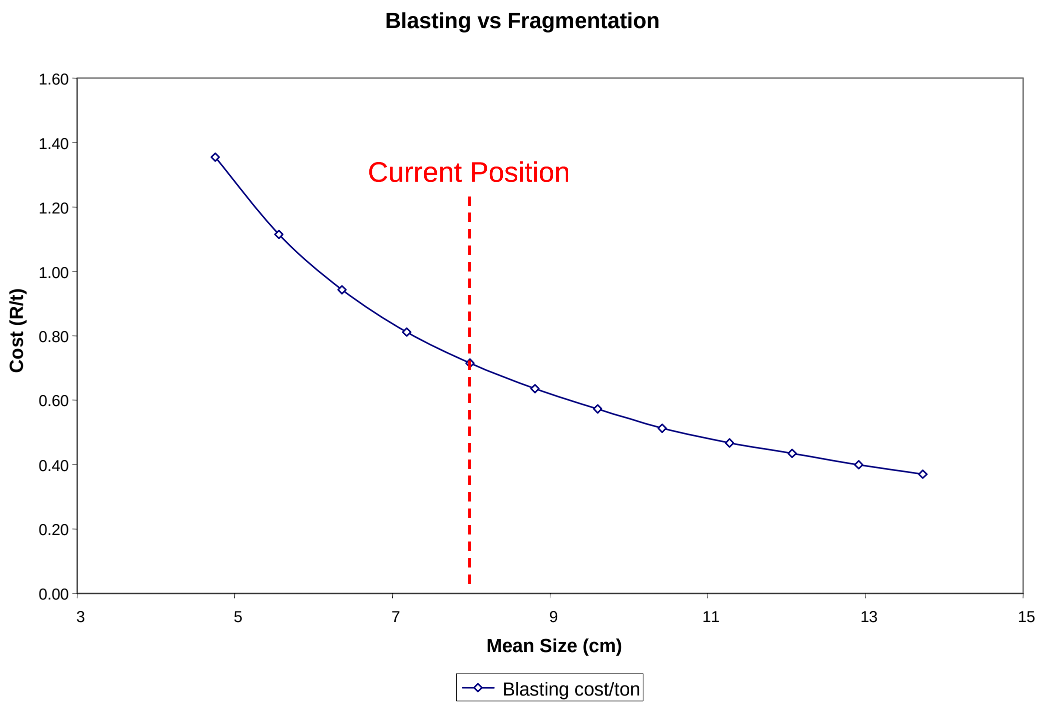

Figure 9: Blasting cost vs. mean fragmentation

The relationship between loading, hauling and secondary equipment costs and fragmentation distribution is not as clearly definable as with blasting and drilling. Before a relationship could be defined, it was necessary to make a number of assumptions.

The instantaneous loading rate is measured on the loading shovel and captured in the mine planning records. This rate is used as a measure of machine efficiency. In the short term, this rate will affect the net loading cost per ton as this cost is calculated from the equation:

$$Tons / hr = \frac{Cost\ \ per\ hour}{Cost\ \ per\ ton}$$

The first necessary assumption for loading is the relationship between mean fragmentation and loading cost. In order to determine this relationship, case studies, such as the one conducted by Bellairs, were investigated. Graphs similar to the example shown in figure 1 were discussed, but no numeric relationship was found and therefore, initially, a rather broad-based assumption was necessary. During discussions with Thabazimbi mine management personnel[2], a number of different scenarios were represented with graphs for loading versus fragmentation size. Initially it was felt that a parabolic shaped curve was necessary, signifying an optimal lowest point with higher costs for both excessively fine material (the engineering component of loading costs increases due to excessive dust in the machinery – air filters, oil filters etc.) and excessively coarse material. In order to validate any assumed graph shape, it would be necessary to reproduce such extreme fragmentation sizes in reality. Owing to practical limitations, it was decided to make the focal point for this project a smaller window around the current benchmarked scenario. Further thought was then given to the required shape of the curve not only for loading, but also for secondary equipment and hauling as well. Considering a small window of the overall curve was examined (shown in figure 10), a straight-line relationship was deemed to be a satisfactory representation.

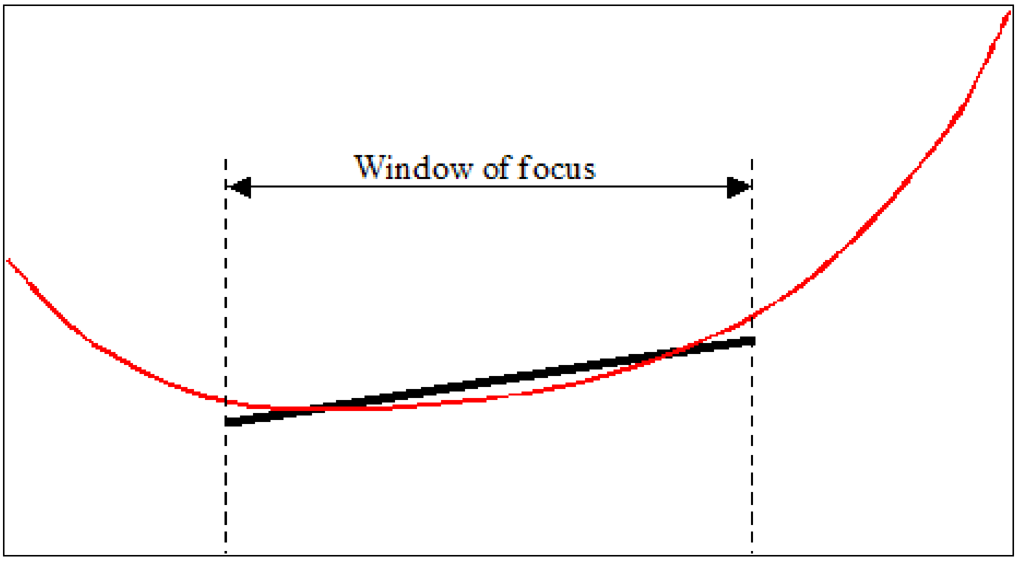

Figure 10: Area of Concern

[2] Discussions with A. Gricius, T. Otto and A. van den Brink at Thabazimbi Mine in 2004.

Firstly, the minimum suitable limit was identified as R0.70/ton and it was decided that for every 1cm change in fragmentation (mean size) the cost per ton would change by R0.065/ton. This relationship was arrived at simply by plotting a straight line at a slope which was thought to be indicative of the effect changing fragmentation may have on loading rates and consequently loading costs. The resultant graphical relationship is shown in Figure 11.

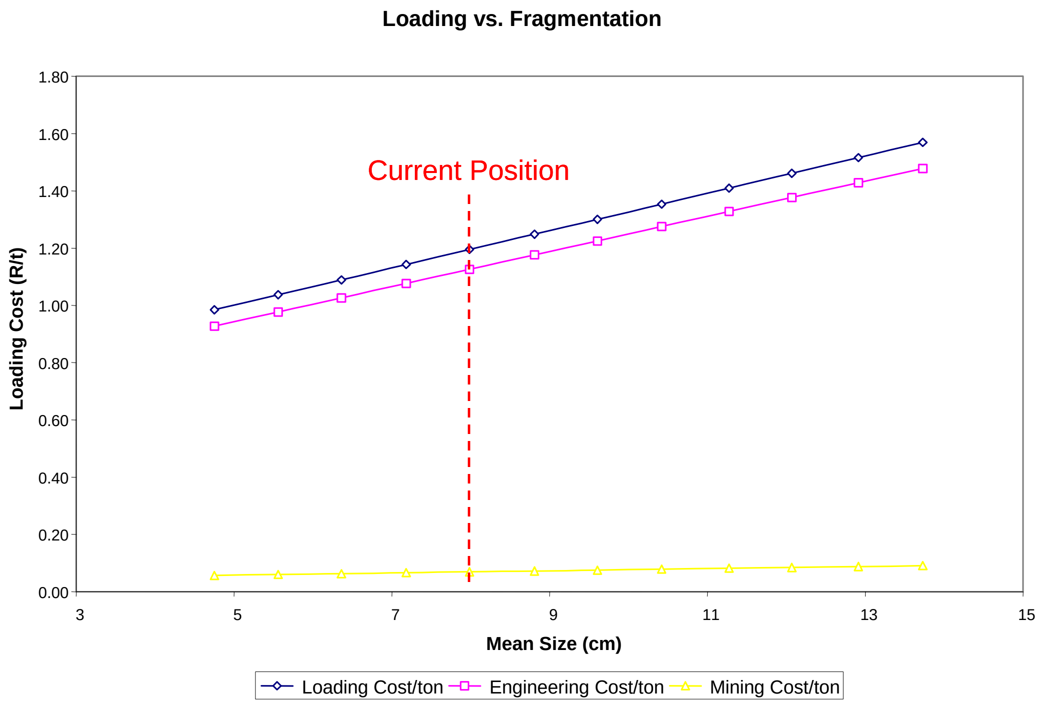

Figure 11: Loading cost vs. mean fragmentation

The impact of changing fragmentation on hauling and secondary equipment is likely to be negligible for minor changes in mean fragmentation size. There should however be some change and for the primary phase of the development of the model, a R0.03/ton change in cost per ton was assumed for every 1cm change in mean fragmentation. For hauling, the minimum suitable limit selected was R1.57/ton and for the secondary equipment, R0.53/ton was considered to be appropriate. Figures 12 and 13 show the generated graphical relationship between hauling and secondary equipment, respectively, and mean fragmentation. The same straight-line principle was applied to the generation of the hauling and secondary equipment graphs. It should again be stressed that these are broad-based assumptions arrived at through thorough discussion with mine management and investigation of data collected during the benchmarking execise.

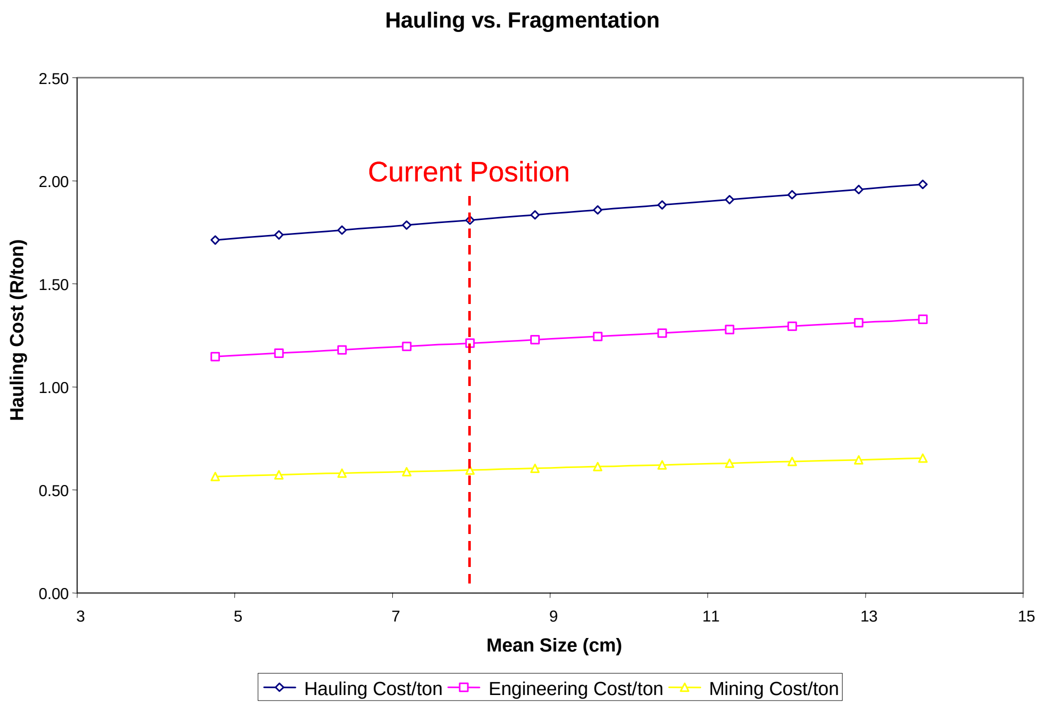

Figure 12: Hauling cost vs. mean fragmentation

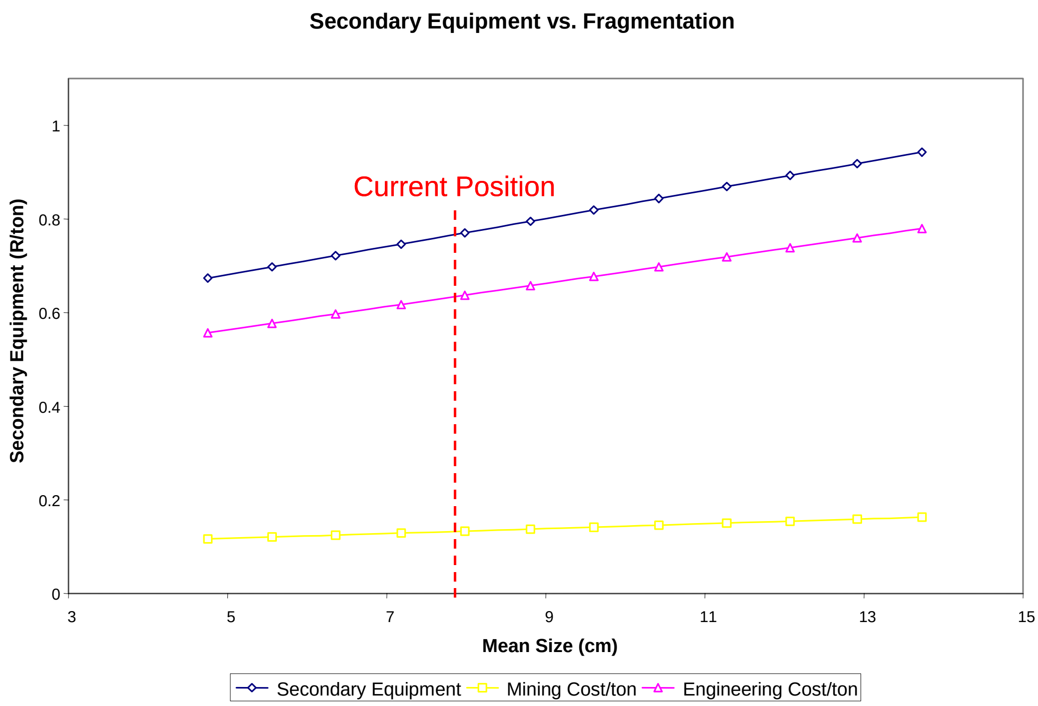

Figure 13: Secondary Equipment cost vs. mean size

For secondary breaking, the mine employs a contractor who uses a pecker (mechanical breaker) machine. The operating cost is calculated and using the fragmentation distribution curves, the tonnage of oversize material (percentage above chosen dimension) generated is predicted. The calculated cost of this oversize is divided by the tonnage broken per hole to determine the cost per ton for a respective mean fragmentation size. Figure 14 shows the relationship between this cost and varying mean fragmentation sizes. It is noticeable that for this operation the cost for secondary breaking is negligible in comparison with the operating costs for the other operations.

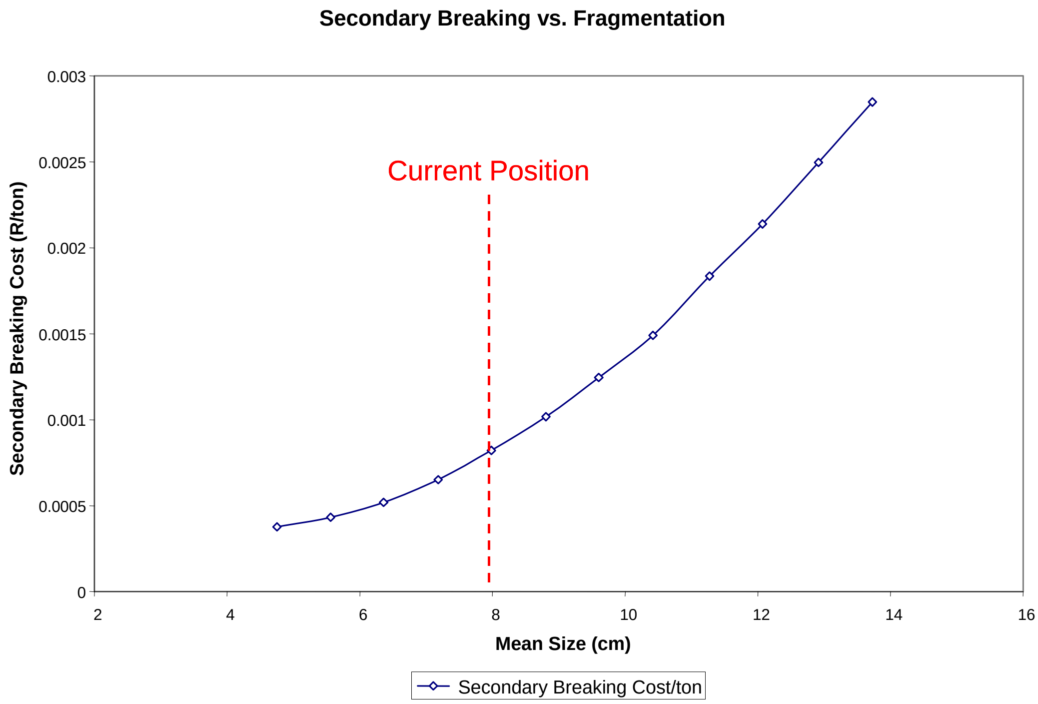

Figure 14: Secondary breaking cost vs. mean fragmentation

The resultant curve, which defines the entire waste mining operation, is simply the sum of all the graphically represented relationships already discussed. The true shape of the graph may or may not differ markedly from the version shown in Figure 15.

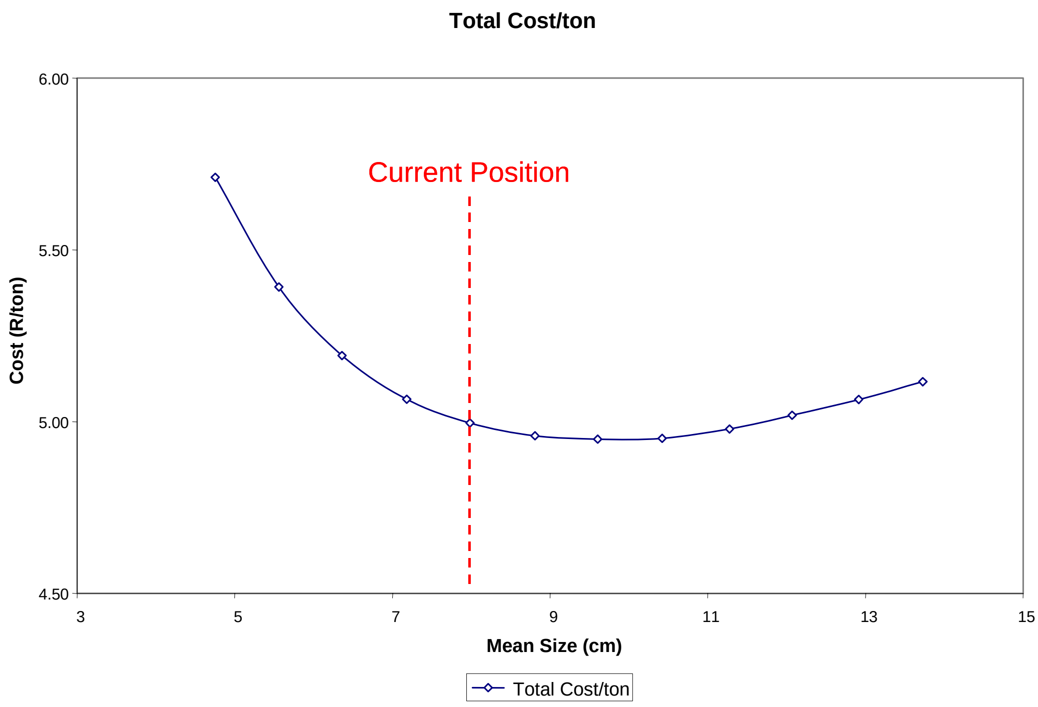

Figure 15: The Model

It is important to note that at this stage the model is dependent on the various assumptions previously discussed and therefore before it can become a working model, validity must be established. However all agree that these parameters do affect operations and the assumed relationships reflect conservative estimates of experienced production personnel. This is better than ignoring the effects for lack of hard data, and provides something against which to measure and improve the model.

The effects of highwall and floor conditions on mining costs as monitored in the benchmark, can only be determined in the longer term. The implementation of a change to the blast design in a pit, or across the mine would have to be followed by months of monitoring to determine the financial impact on both mining and engineering components that may be affected by the change.

5.3 Conclusions

The first step in achieving a near optimal mining operation is fully understanding the current operation in terms of the effect of changing variables on efficiencies.

The further development of the prediction model will ultimately allow for accurately forecasting the degree of economic change produced by implementing changes to blast designs or techniques.

6 PROVING THE MODEL

In order to authenticate and establish it's validity of the model, it was necessary to generate varying mean fragmentation sizes and monitor the actual economic effect of this changing fragmentation on all of the mining operations. To generate this change in mean fragmentation, a change in the powder factor was required. Expanding the drilling pattern incrementally generated this change, and for each change, all the parameters relevant to the model were again evaluated.

The drilling patterns, sub-drill, and relevant blast block numbers are detailed in table 6. For consistency, the remaining blast parameters and the general area, size and shape of the blast blocks were, as far as was practical, kept consistent with the benchmark. The inter-row and intra-row delays for the timing designs were maintained. However, the point of initiation did vary, depending on the number of free faces. See Appendix 4 for the layout and timing design for all the test blasts.

Table 6: Parameters for Test Blocks

Drilling Pattern (m)	Sub-drill (m)	Block No.
7 x 8.1	2.3	1000/16; 1000/18; 1000/20
7.3 x 8.5	2.4	990/06; 990/11
7.6 x 8.8	2.5	990/09
7.9 x 9.2	2.6	990/35

6.1 Results

The overall impression of the blast results for the pattern expansion test blocks at Donkerpoort West were good, with no obvious deterioration in fragmentation from the benchmark. This was supported by feedback from the load and haul team, garnered in feedback meetings held approximately 2 weeks subsequent to every blast, once the majority of the blasted block had been loaded out. The blast plans are included in Appendix 4.

6.1.1 Geology

A decision was made to conduct all test blasting in areas with similar geological conditions and in line with the geology encountered during the benchmark blasts. As such, the formation for all the blocks blasted consisted of between 95% and 100% Banded Ironstone Formation (BIF), which is currently predominantly a waste material at Thabazimbi with an average density of 3.2g/cm³. The balance of material was made up of diabase, shale, and waste dump material, usually softer material than BIF and with a density of approximately 2.2 g/cm³.

6.1.2 Fragmentation

Figure 16 shows the measured fragmentation curves on a percentage passing vs. indicated size graph for each of the test blasts (detailed results in Appendix 3). It can be seen that with an increase in drilling pattern, although not obvious to the human eye, the resultant fragmentation distribution was coarser than the benchmark curve, with the exception of blast block 990/11, which was in a different area of the pit to the remaining blocks. Here the fine fragmentation could be attributed to the geology encountered in this particular area.

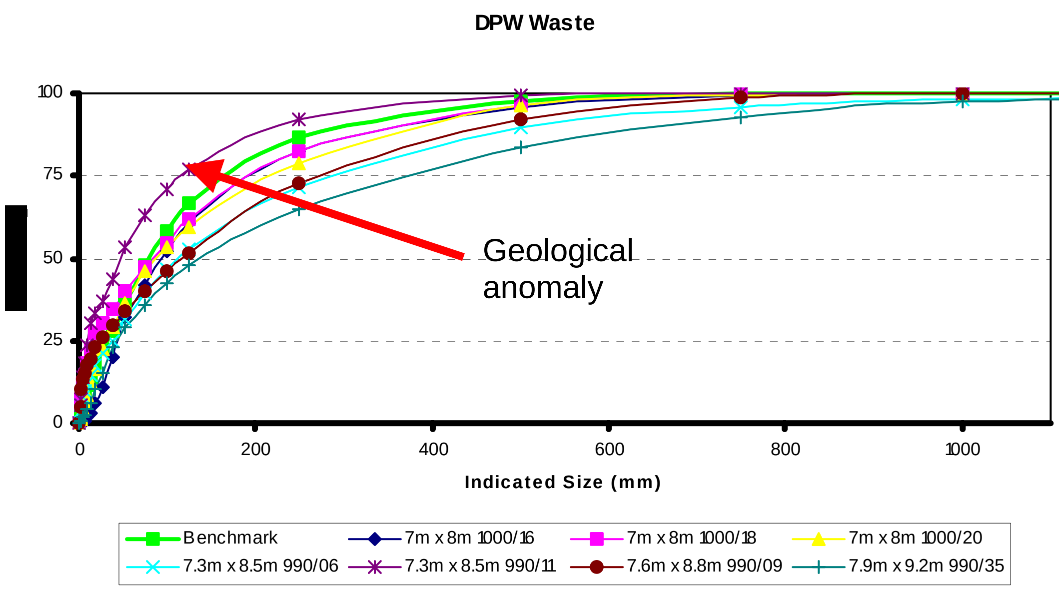

Figure 16: Summary of Fragmentation Distribution Curves

Table 7 is a summary of the uniformity index and mean size of the muckpiles generated for each blast. Again it can be seen that the mean size is markedly lower for 990/11 (highlighted in blue) than any of the other blasts. Consequently the results from this block were excluded as geologically controlled.

Table 7: Fragmentation Summary

	Benchmark 1000/4	1000/16	1000/18	1000/20	990/06	990/11	990/09	990/35
Uniformity Index n	0.9	1.04	0.73	0.86	0.76	0.73	0.79	0.64
Mean Size (mm)	79.86	93.75	83.73	87.44	113.01	47.22	89.6	137.4

6.1.3 Loading Performance

The loading rates are the average instantaneous loading rates for the loading of the entire muckpile of a blast. In table 8, the final loading rate for each blast is detailed. Noticeable from these results is the apparent random nature of the loading rates. This may be attributed to moderately different geological conditions, different drill rigs or different operators. It is important to note that the general trend does not show a dramatic decrease in loading rates.

Table 8: Donkerpoort West Loading Rates

	Benchmark 1000/4	1000/16	1000/18	1000/20	990/06	990/11	990/09	990/35
Loading (Tons/hr)	1005±233	1233	1302	1177	987	1760	775	1132

* Highlighted in blue is a possible anomaly – block 990/11

6.1.4 Other Results

The effect of these pattern changes on the remaining operations such as hauling and secondary equipment is taken to be consistent with the original assumptions made in the initial model.

6.2 <u>Application of Results</u>

In order to generate the ‘actual’ curve defining the mining operation at Donkerpoort West Pit, these results had to be introduced into the model. The actual fragmentation mean sizes for each test blast and the resultant loading rates were entered into the model and the new graphs were generated.

With the introduction of the mean fragmentation sizes after all the test blasting, the model was re-calibrated resulting in adjusted fragmentation distribution for each design and as such a slight shift in all of the resultant curves. This was achieved by adjusting the rock factor (A) shown in figure 7 from 1.92 to 2.2 to yield mean sizes approximating the measured sizes shown in table 7.

The drilling and blasting cost per ton is calculated automatically by the model based on unit explosive and initiation system prices entered into the model.

As mentioned in the previous section, the model uses the recorded loading rates to calculate the loading cost per ton. Figure 17 shows the plot of the loading cost per ton for each of the blasts as well a trend line of these points. The equation of this trend line, $y = 0.0269x + 0.9065$, is then used to generate the new ‘actual’ loading cost per ton versus mean size line. It can be seen that this line is not as steep as the initial assumed line but still has a positive slope indicating increasing loading cost with increasing coarseness in fragmentation.

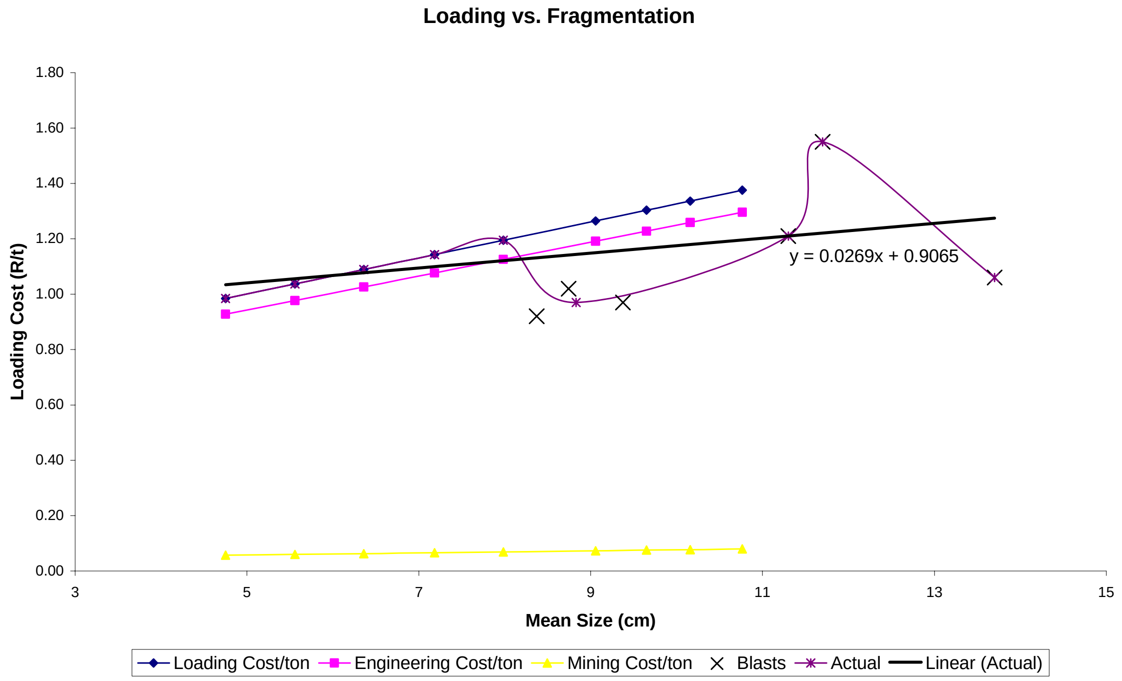

Figure 17: Redefined Loading vs. Fragmentation Graph

The resultant total cost versus fragmentation curve is shown in figure 13. Also shown, is the original curve to highlight the differences between predicted and actual. It is apparent that the increase in mean fragmentation size (applied to the model through the increase in the value of the rock factor) has resulted in a shift in the position of the curve. This adjusted rock factor was applied to all the test blasts, including the benchmark, as there was an increased confidence in this number, arrived at through more extensive test work than was carried out for the benchmark. In effect the position of the benchmark is shifted slightly in terms of mean size but the total cost per ton at this point (R5/ton) is comparable with the original benchmark (R5.04/ton).

This adjustment in mean size coupled with the new loading curve has resulted in increased costs per ton to the left of the adjusted benchmark and marginally lower costs per ton to the right of the adjusted benchmark, compared to the original predicted curve.

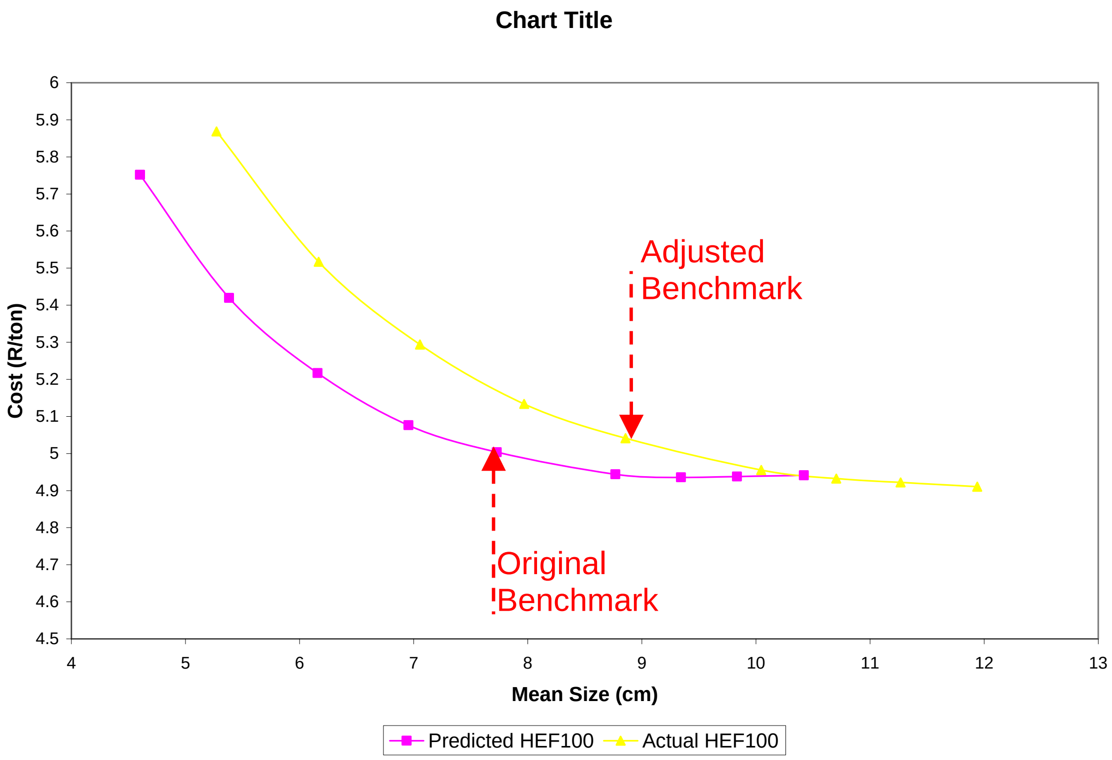

Figure 18: Redefined Total vs. Fragmentation Curve

The validated model suggests that there is room for improvement by reducing powder factors and generating larger mean fragmentation sizes, while reducing the overall cost per ton from R5.04/ton down to R4.91/ton. Assuming an annual waste mining tonnage of 30Mtons, this equates to a saving of R3 900 000/year.

6.3 <u>Discussion</u>

It is reasonable to assume that with ever-increasing fragmentation the resultant cost per ton will ultimately reach a point where an exponential increase will be experienced. The model shows no indication of this for the fragmentation sizes considered here (figure 18). This is in line with the assumption made, during the initial development of the model, that only a narrow window of the total possible fragmentation size generation will be considered. This was done due to practical limitations, where blasting to generate larger fragmentation sizes is restricted.

The exercise of validating the model has delivered a tool, which could be used to compare the effect of different blast designs on the efficiency of the overall operation. To further validate the model, the actual effect of varying fragmentation (as negligible as it may be) on hauling and secondary equipment costs, should also be determined. This would require a long-term process of producing different fragmentation sizes and monitoring the effect of this on the equipment costs, particularly the engineering component of this cost and the tyre component from a mining point of view.

The tool is capable of giving a good indication of what the most effective blast design or explosive would be to deliver the most efficient operation.

6.4 Conclusion

The first step in achieving continuous improvement in the mining operation is understanding the current operation in terms of the effect of changing variables on efficiencies.

The further development of this proven model will ultimately allow for more accurately forecasting the degree of economic change produced by implementing changes to blast designs or techniques.

6.5 Recommendations

The model implies a more efficient operation with an increase in drilling pattern. A decision should be made as to which pattern yields the most favourable result. This pattern should be introduced at Donkerpoort West for an extended period of time to further substantiate these findings.

Consequently, thought should be given to the remainder of the operation where currently the majority of blasting is conducted using ANFO. This research project suggests that the introduction of an explosive with a higher density and relative bulk strength than ANFO, such as P700, into the remaining pits (with similar pattern expansions) would result in similar improvements in efficiencies.

6.5.1 Change of Explosive

The proven Donkerpoort model has been used to compare the efficiency of the operation with the introduction of different explosives. In figure 19, P700, which is a doped emulsion (65% emulsion, 35% Ammonium Nitrate prill blend), is compared with ANFO and HEF100, a pure emulsion. The lower unit costs coupled with higher relative effective energy of ANFO and P700 result in a more efficient operation when compared with HEF100. Although the unit costs for ANFO and P700 differ dramatically (~R1.80/ton versus ~R2.30/ton respectively), the model shows that, with the improved fragmentation generated by the blend product, a lower overall cost per ton will result if the pattern is expanded beyond the current pattern of 6.4m x 7.4m. The difference between the minimum cost per ton on the ANFO curve and the P700 curve is R0.03/ton which equates to cost savings of around R900 000 a year, assuming 30Mtons of waste are mined in one year. In addition to this, due to the finer fragmentation produced when blasting with P700, wear on machinery should be reduced, which, over an extended period should lower mining and engineering costs.

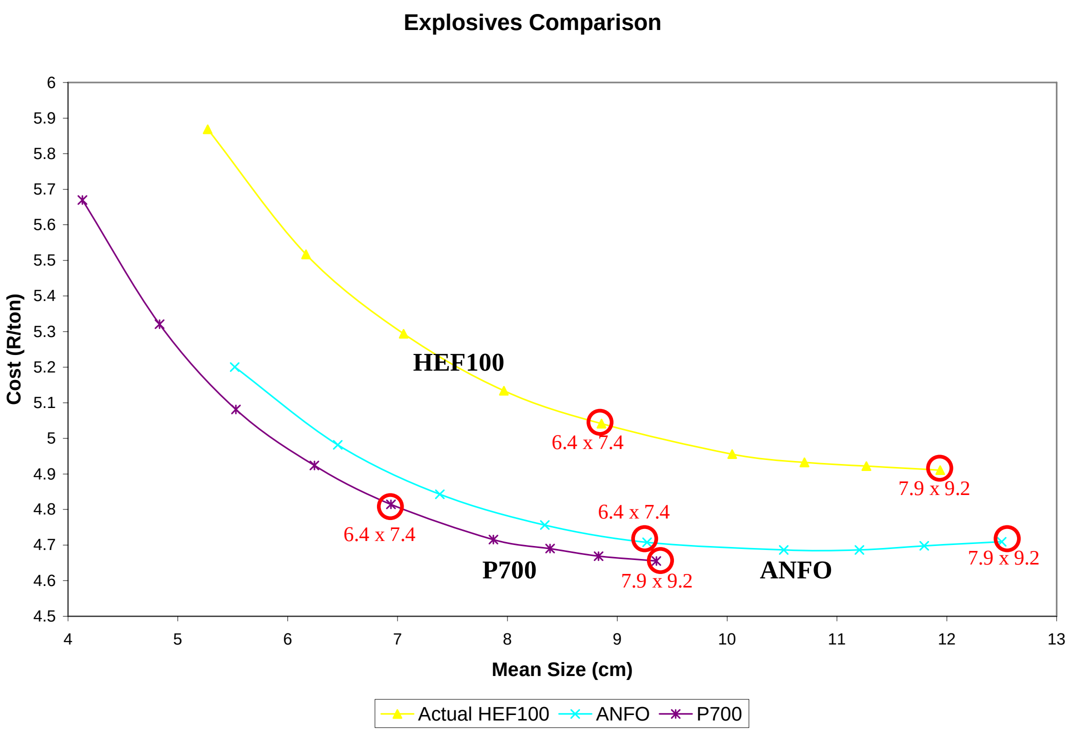

Figure 19: Cost Comparison of Various Explosives

6.5.2 Change of Initiation System

Electronic detonators have delivered a number of improvements to various operations around the world (Appendix 1). These proven results have shown an increase in uniformity of the muckpile with a reduction in fines and oversize material. Due to this increased uniformity, a factor of 1.3 is applied to the measured uniformity index in the model (explained in Chapter 2). The economic effect of this is illustrated in figure 20 with mean size on the x-axis replaced with 80% passing. This change in the measure of fragmentation is done, as theoretically speaking, applying a positive change to the uniformity index does not affect the mean size, but reduces both fines and oversize percentages. The marked reduction in oversize material, with the introduction of electronic timing, results in a significant lower cost per ton for the mining of this coarser material. The consequence of this would be a further reduction of overall mining costs.

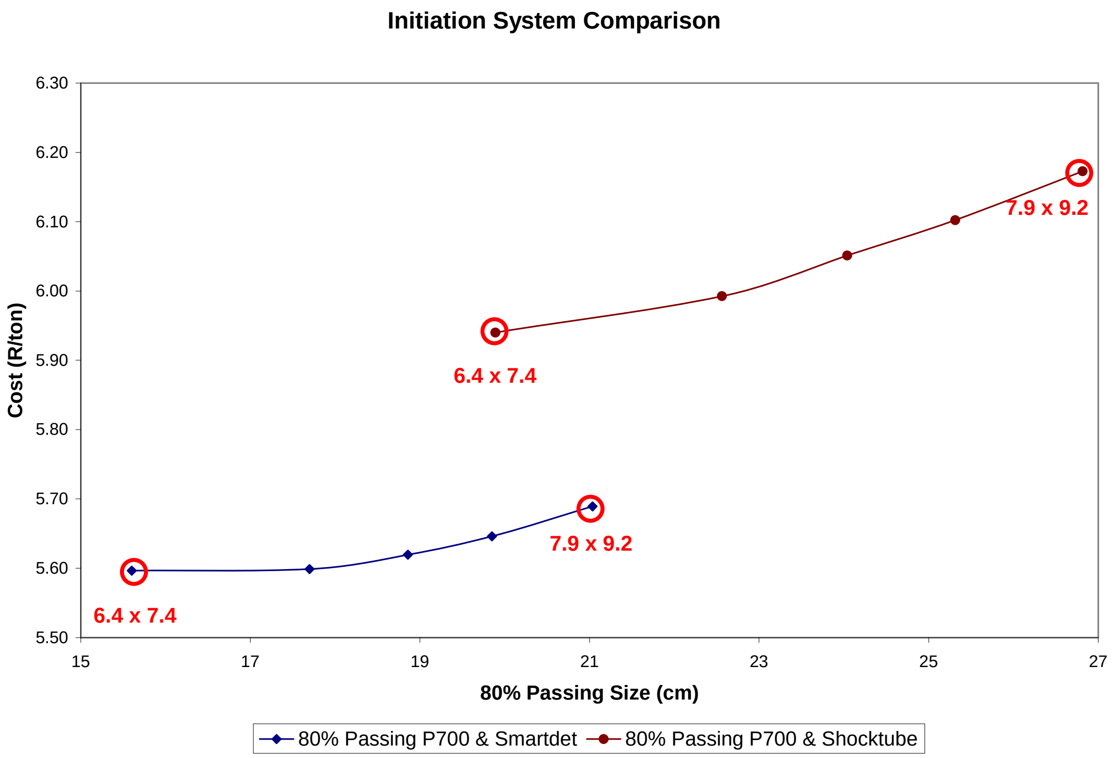

Figure 20: Shock Tube vs. Smartdets at 80% Passing

This option would require further test work to develop confidence in the assumptions made in the model concerning the effect of timing accuracy on fragmentation.

If the decision is taken to implement either or both of these options, the model could be further validated by monitoring the consequences of any changes experienced over a period of time. It is important to note that mining conditions (equipment, rock properties etc.) will always be in a state of change and it is therefore necessary, in this process of continual improvement, to constantly monitor all the processes in the operation.

It must be remembered that the results of the test work will be relevant only to Thabazimbi. The site conditions encountered here are unique and if this model is to be employed at different sites with differing geological conditions, explosives or equipment, then all the data related to the new site will have to be captured and entered into the model.

7 CONCLUSION

The intention of this project is to implement a step change in mining efficiencies at Thabazimbi Iron Ore Mine, through the application of new ideas and attention to the blasting operation.

The importance of blasting and its relationship to the efficiency of the entire mining operation is widely acknowledged. The core focus of this project was defining this relationship and consequently determining key areas where efficiency could be uplifted.

The result was the development and validation of a tool or model based on the defined relationship between fragmentation sizes and operating costs per ton accross the relevant mining operations.

Ultimately the proven model was used to identify areas of opportunity for improvement. The implementation of a doped emulsion and an appropriate expanded pattern, which would replace ANFO across the mine, was shown by the model to have a potential for improving efficiencies across the mine. Considering the level of confidence in the model at this early stage, this would be the obvious first step, and the consequent monitoring of any changes in operational efficiency would build further confidence into the model.

The second option of implementing electronic detonators would require further test work to increase confidence in the assumptions made in the model concerning the effect of timing accuracy on fragmentation in the rock formation encountered at Thabazimbi.

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9 APPENDICES

9.1 Appendix 1

Some of the operations that have introduced Smartdet® and the benefits that they have realised are listed below. These do not include applications where it is used exclusively for environmental considerations.

1. Site: Optimum Colliery (BHP/Billiton), South Africa
   Large Strip mine (8 Draglines) with hard overburden, 13Mt coal p.a. Smartdet® introduced from May 2000, now fully converted for overburden (Hough, 2001).

Area of Benefit	Gain
Drill capacity	31%
Explosives cost reduction	40%
Dragline cycle, seconds	78 to 71.5
Vibration triggers per month (1mm/s, 120dB)	40 to 10

2. Site: Damang Gold Mine (African Mining Services, AMS), Ghana
   17Mt.p.a. Open pit operation. Smartdet® introduced progressively from 2000 and now fully converted (Baka Abu, 2002).

Area of Benefit	Gain
Phyllite productivity	11%
Dolerite productivity	22%
Sandstone productivity	21%
Crusher throughput	10%
Vibration reduction, mm/s	3.4 to 1.6
Airblast reduction, dB	127 to 108

3. Finsch Diamond Mine (De Beers), South Africa.
   Blasting results from Smartdet® have resulted in a more uniform rock size distribution. (Simon Tose, Cor Baltus, 2002)

4. Peak Quarry (Lafarge), South Africa.
   (Gayonn Bedser, 1998)

Area of Benefit	Gain
Oversize generation	Reduced to less than 0.2% of blasted volume
Fragmentation	Mean ROM size reduced from 53mm to 26.5mm

9.2 Appendix 2

In recent years a number of software packages have been developed with which to measure the rock size distribution using optical means. These basically work as follows:

1. A series of images are collected of the blast muck pile, either/and before, during loading or at some point in the ore handling process. A scaling object of known size must be placed on the muck pile and captured in each image and care must be taken to avoid excessive shadows or contrast between the light and dark areas in the images.

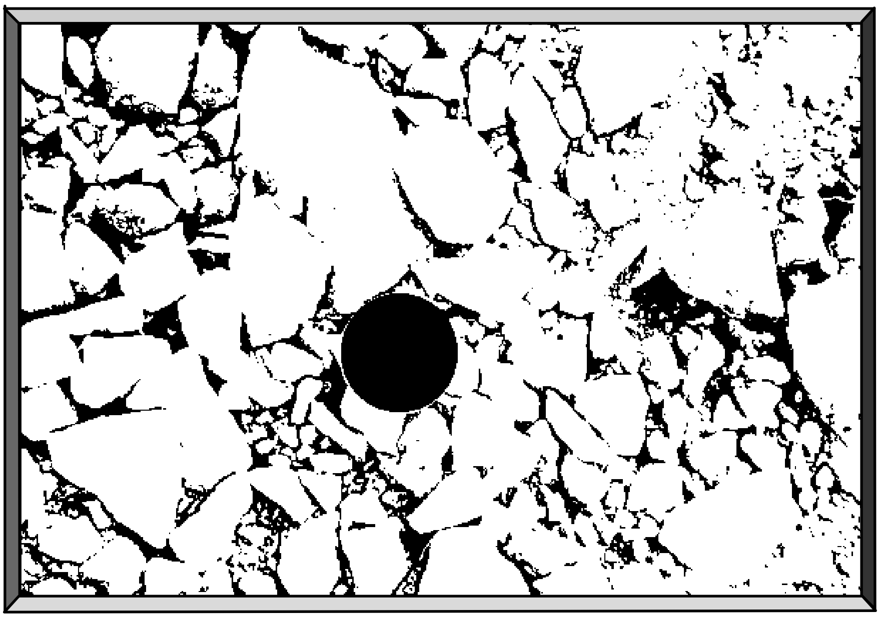
2. Photographs are turned into digital images by scanning or digital images are obtained directly from a digital camera or are captured as still frames from a video camera.

3. The digital images are processed using the chosen software. After the scaled object, tennis, football etc is identified and blanked out, the digital image may be edited to identify areas of fines, large boulders etc.

4. The software tends to be unable to differentiate shadows, multi-coloured fragments, overlapping fragments, foreign objects, sticks, cables, etc. Some 5 to 10 minutes of editing per image may be required to assist in the correct

interpretation of the fragmentation. Poor images may demand 30 minutes – hence the need for quality.

Editing protocol:



- Merge large particles that were over-divided
- Delineate large particles that were under divided
- Delineate small particles that were under divided
- Areas of fines
- Unwanted objects - sky, bench, highwall etc.
- System calibration, once set should only need to be tweaked for each site

5. Once all the images from the muck pile have been edited, they are combined into a single batch file and the sizing is done. This can take several hours of processing time per batch of images and requires dedicated computer hardware. What results is a size distribution of the photographic images.

When used correctly, with quality images, the fragmentation software will give a rapid and meaningful indication of the size distribution of the sampled muck pile. This can be used effectively to compare different blast results and track the changes seen.

AEL uses the software with a Rosin Rammler curve fitted to the measured data. The Rosin Rammler equation incorporates a uniformity index and characteristic size. The equation is as follows: -

$$R = e^{-\left({}^{X}/_{Xc}\right)^{n}}$$

where : R = proportion of material retained on the screen
X = screen size
Xc = characteristic size (63.2% passing)
n = uniformity index

It is important to understand that current optical methods of fragmentation analysis use two-dimensional images of the muck pile. The software detects the sides of rock fragments and then, using the known size of the scaling object, separates the fragments in each image into different size groups.

Each fragment is sized according to the smallest dimension and each fragment is weighted according to the area of the fragment. The result is a distribution showing the percentage of the total area, which would pass through the different size grids. The size is always referred to as the *indicated size*. This is because it is the two dimensional size (it is measured from a two dimensional photograph) and not the three-dimensional size as measured if the same sample of rock was physically passed through a series of sieves. The software makes no attempt to assume or calculate the third dimension.

Studies carried out using this type of software have shown it to be a powerful tools. It can be rapidly used to measure many different situations, for example:

- the effect of changing an initiation system,
- results from different drilling patterns in similar ground conditions,
- the effect of different fragmentation on loading cycle or crusher efficiency,
- an objective tracking of fragmentation changes as a result of different explosives.

Spreadsheet description:

The spreadsheet contains the sheets:

1. Summary.

2. Control – Register of images received and information received.

3. % Passing Graph. X-axis is the indicated size (mm) and the y axis % Passing.

4. % Retained Graph. X-axis is the indicated size (mm) and the y axis %

Retained.

5. Data. The uniformity index and characteristic size, Xc, (63.2% passing) for the Rosin Ramler curves are listed.

It is normally desirable to have uniform fragmentation, thereby avoiding both excessive fines and oversize fragments in the broken ore. The Uniformity index (n) in the Rosin-Ramler equation gives a measure of this with values greater than 1, indicating a more uniform sizing, whilst lower values result in higher proportions of fines and oversize.

We create a combined result based on each of the blasts monitored under the same basting parameters to give us the size distributions as either % Passing or % Retained.

The P20 is the typical size of the rock for 20% of the sample.

% Retained Graph. X-axis is the indicated size (mm) and the y-axis % Retained. The bar represents each individual sample under the same blasting parameters. This is where we ensure the consistency of each blast sample. The line represents the analysis of all the samples monitored.

9.3 Appendix 3

Benchmark		
Images	45	
Xc	101.54	mm
n	0.90	
Size (mm)	% Passing	% Retained
0	0.00	2.70
1	2.70	1.13
2	3.83	3.07
5	6.90	1.89
7	8.79	2.44
10	11.23	2.86
13	14.09	3.90
19	17.99	4.34
27	22.33	5.35
38	27.68	8.66
53	36.34	11.35
75	47.69	10.74
100	58.43	8.07
125	66.50	20.19
250	86.69	11.14
500	97.83	1.98
750	99.81	0.19
1000	100.00	0.00
2000	100.00	0.00
4000	100.00	0.00
Totals		100.00

7m x 8m 1000/16		
Images	80	
Xc	125.43	mm
n	1.04	
Size (mm)	% Passing	% Retained
0	0.00	0.05
1	0.05	0.02
2	0.07	0.32
5	0.39	0.39
7	0.78	0.75
10	1.53	1.39
13	2.92	2.95
19	5.87	5.09
27	10.96	9.29
38	20.25	11.94
53	32.19	9.92
75	42.11	10.29
100	52.40	8.32
125	60.72	21.68
250	82.40	13.52
500	95.92	3.26
750	99.18	0.79
1000	99.97	0.03
2000	100.00	0.00
4000	100.00	0.00
Totals		100.00

7m x 8m 1000/18		
Images	38	
Xc	125.28	mm
n	0.73	
Size (mm)	% Passing	% Retained
0	0.00	5.78
1	5.78	1.37
2	7.15	4.90
5	12.05	2.79
7	14.84	3.48
10	18.32	3.93
13	22.25	5.18
19	27.43	2.78
27	30.21	4.08
38	34.29	5.60
53	39.89	7.41
75	47.30	7.50
100	54.80	6.72
125	61.52	21.17
250	82.69	13.72
500	96.41	3.59
750	100.00	0.00
1000	100.00	0.00
2000	100.00	0.00
4000	100.00	0.00
Totals		100.00

7m x 8m 1000/20		
Images	71	
Xc	125.58	mm
n	0.86	
Size (mm)	% Passing	% Retained
0	0.00	1.28
1	1.28	0.54
2	1.82	2.57
5	4.39	1.79
7	6.18	2.52
10	8.70	3.19
13	11.89	4.72
19	16.61	5.58
27	22.19	6.61
38	28.80	7.64
53	36.44	9.36
75	45.80	7.79
100	53.59	5.83
125	59.42	19.32
250	78.74	17.70
500	96.44	3.16
750	99.60	0.40
1000	100.00	0.00
2000	100.00	0.00
4000	100.00	0.00
Totals		100.00

7.3m x 8.5m 990/06		
Images	59	
Xc	126.62	mm
n	0.76	
Size (mm)	% Passing	% Retained
0	0.00	3.68
1	3.68	1.54
2	5.22	2.96
5	8.18	1.73
7	9.91	2.12
10	12.03	2.39
13	14.42	3.14
19	17.56	3.36
27	20.92	4.02
38	24.94	6.59
53	31.53	8.09
75	39.62	7.27
100	46.89	5.73
125	52.62	19.16
250	71.78	17.65
500	89.43	6.24
750	95.67	2.21
1000	97.88	2.12
2000	100.00	0.00
4000	100.00	0.00
Totals		100.00

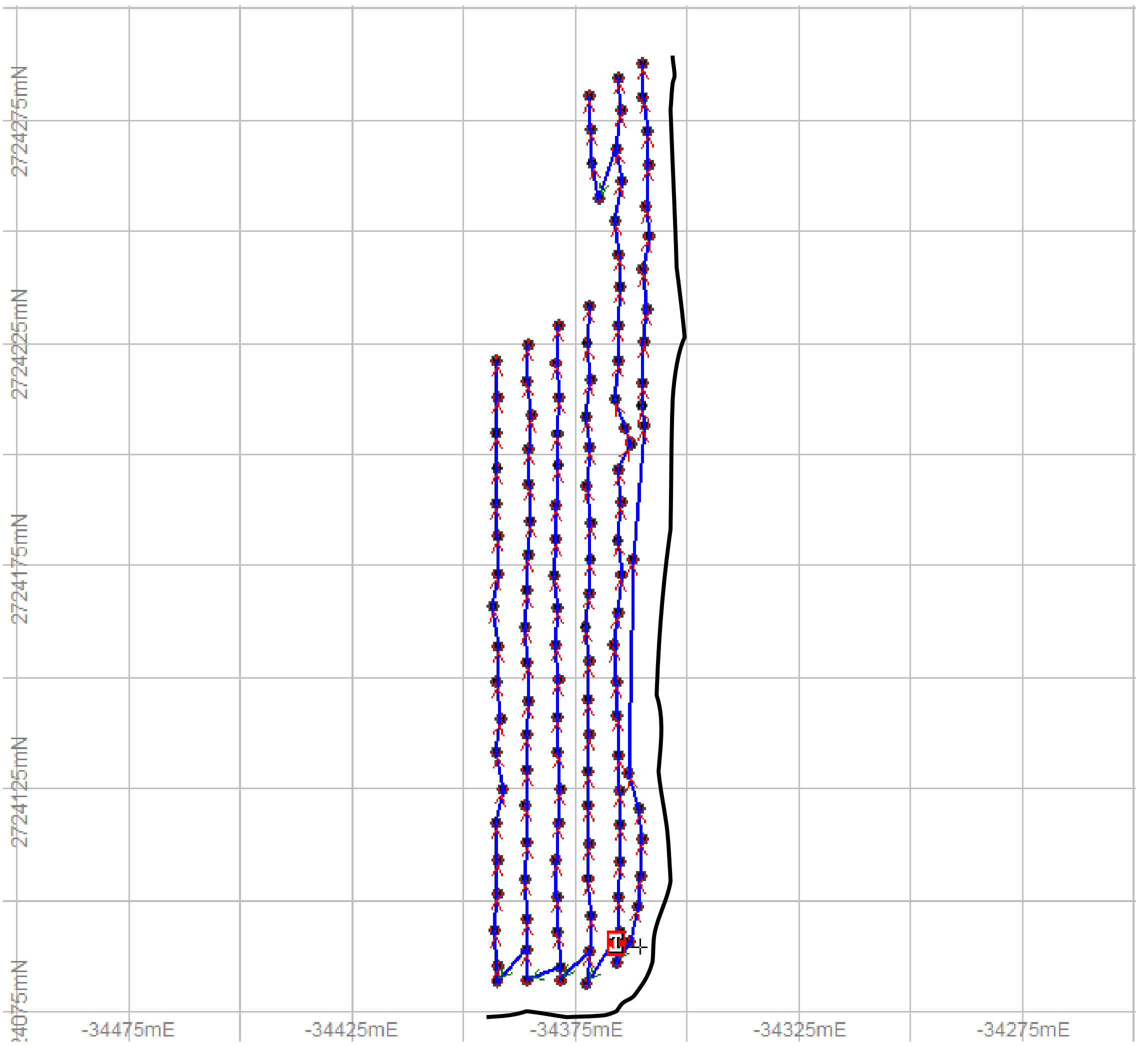
7.3m x 8.5m 990/11		
Images	74	
Xc	57.42	mm
n	0.73	
Size (mm)	% Passing	% Retained
0	0.00	5.55
1	5.55	1.69
2	7.24	6.81
5	14.05	4.19
7	18.24	5.46
10	23.70	6.45
13	30.15	3.40
19	33.55	3.72
27	37.27	6.47
38	43.74	9.64
53	53.38	9.91
75	63.29	7.69
100	70.98	5.84
125	76.82	15.59
250	92.41	7.05
500	99.46	0.54
750	100.00	0.00
1000	100.00	0.00
2000	100.00	0.00
4000	100.00	0.00
Totals		100.00

7.6m x 8.8m 990/09		
Images	50	
Xc	126.95	mm
n	0.79	
Size (mm)	% Passing	% Retained
0	0.00	5.12
1	5.12	5.15
2	10.27	3.25
5	13.52	1.83
7	15.35	2.20
10	17.55	2.14
13	19.69	3.36
19	23.05	3.24
27	26.29	3.58
38	29.87	4.34
53	34.21	6.09
75	40.30	6.01
100	46.31	5.23
125	51.54	20.93
250	72.47	19.51
500	91.98	6.79
750	98.77	1.23
1000	100.00	0.00
2000	100.00	0.00
4000	100.00	0.00
Totals		100.00

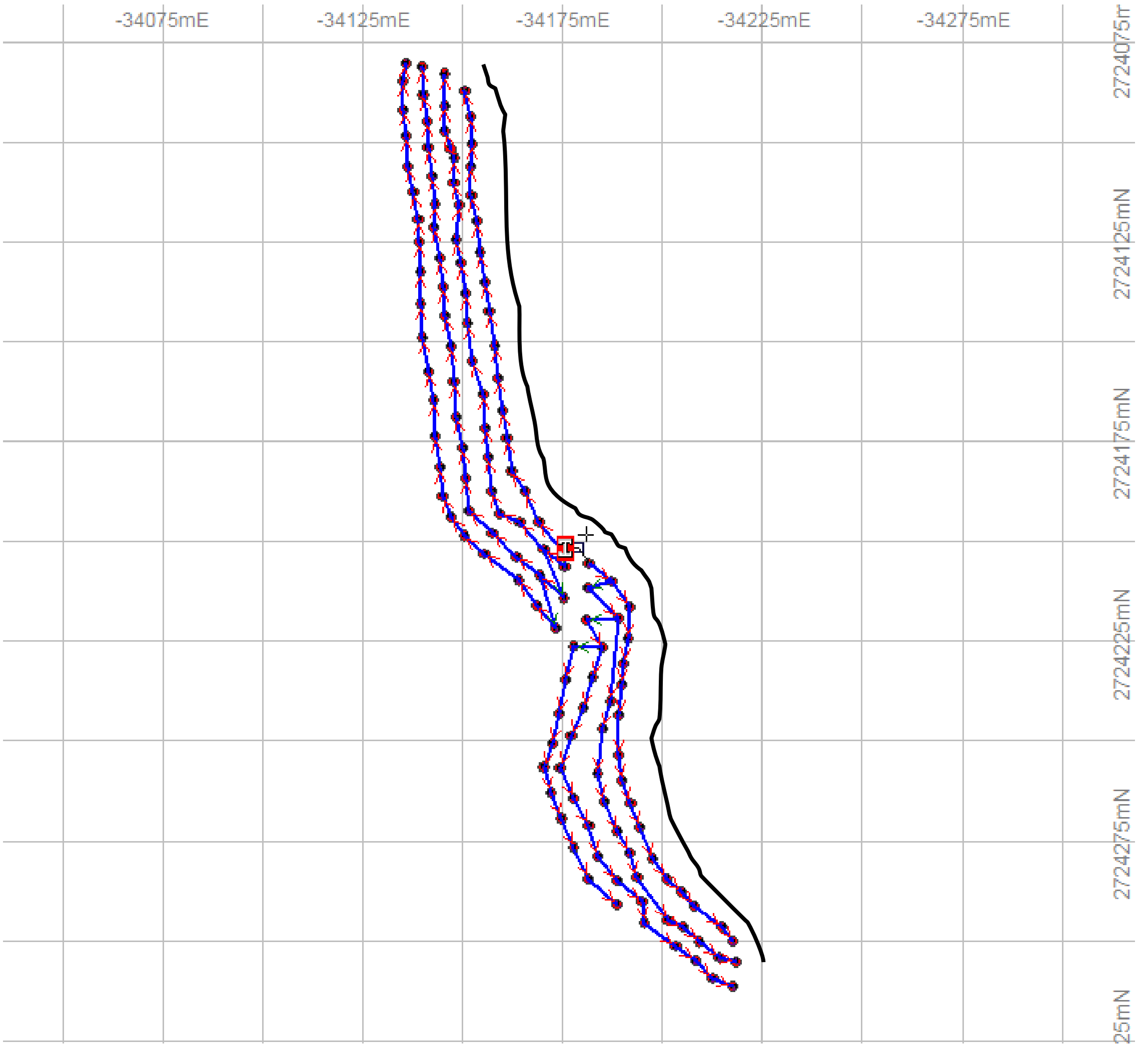
7.9m x 9.2m 990/35		
Images	68	
Xc	127.15	mm
n	0.64	
Size (mm)	% Passing	% Retained
0	0.00	0.34
1	0.34	0.14
2	0.48	1.05
5	1.53	0.95
7	2.48	1.54
10	4.02	2.26
13	6.28	3.85
19	10.13	5.30
27	15.43	7.82
38	23.25	5.97
53	29.22	6.81
75	36.03	6.46
100	42.49	5.25
125	47.74	17.37
250	65.11	18.50
500	83.61	9.19
750	92.80	4.65
1000	97.45	2.55
2000	100.00	0.00
4000	100.00	0.00
Totals		100.00

9.4 Appendix 4

DPW1000/16

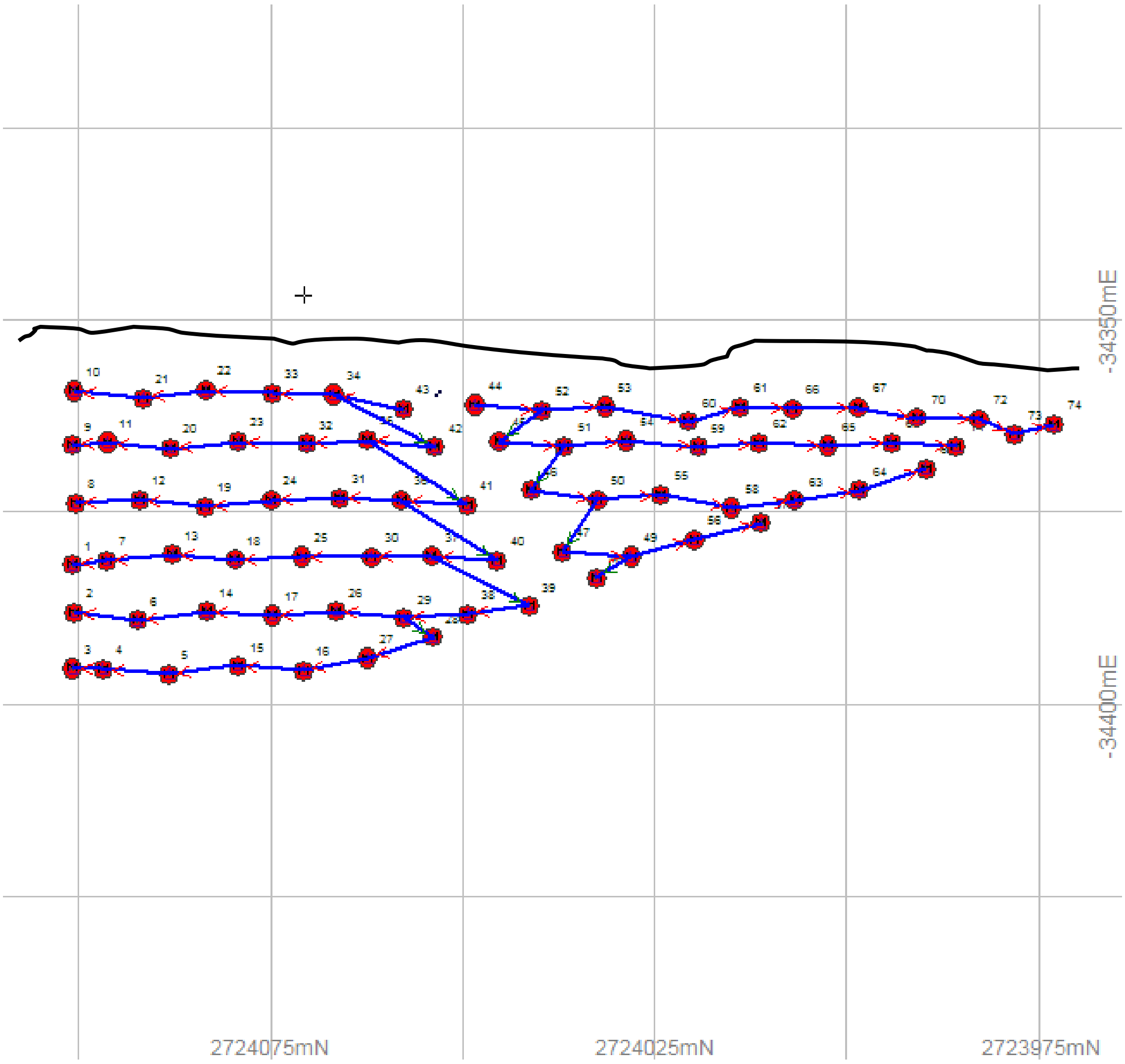


DPW1000/20

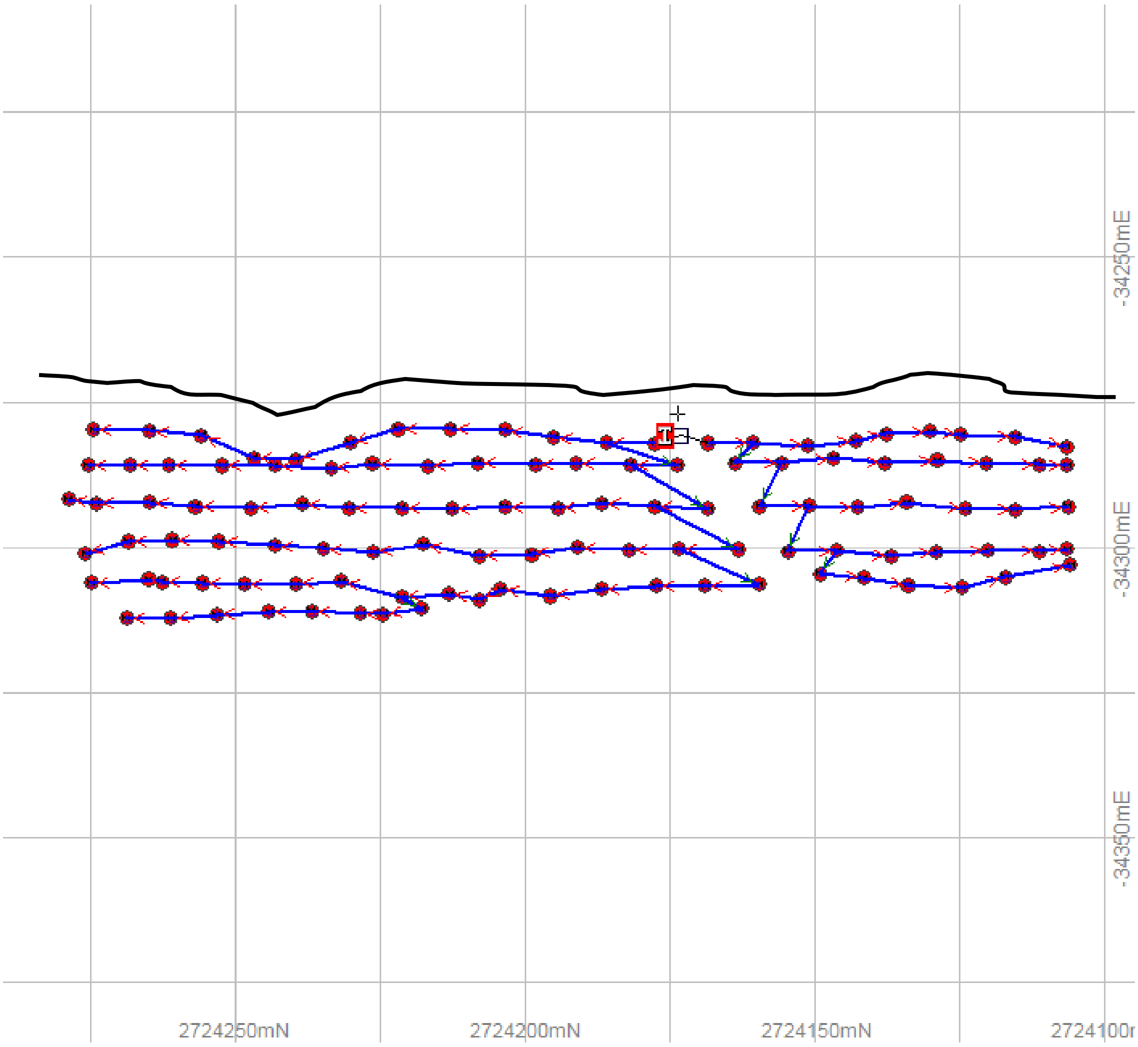


-34075mE
-34125mE
-34175mE
-34225mE
-34275mE
2724075m
2724125mN
2724175mN
2724225mN
2724275mN
25mN

DPW 990/06



DPW990/09


-34250mE
-34300mE
-34350mE
2724250mN
2724200mN
2724150mN
2724100r

DPW990/11


-34200mE
-34250mE
-34300mE
-34350mE
2724100mN
2724150mN
2724200mN
2724250mN

DPW 990/35